PB83-231480

Review of the Preference-Avoidance Responses of Fishes to Aquatic Contaminants

(U.S.) Corvallis Environmental Research Lab., OR

1983

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completi...

1. REPORT NO.	2.	3.
EPA-600/J-83-022		PB83-231480

4. TITLE AND SUBTITLE	5. REPORT DATE
A review of the preference-avoidance responses of fishes to aquatic contaminants (Journal Version)	1983
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
J.D. Giattina and R.R. Garton	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Environmental Research Laboratory/Corvallis Office of Research and Development USEPA Corvallis, OR 97333	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
same	journal article
	14. SPONSORING AGENCY CODE
	EPA/600/02

15. SUPPLEMENTARY NOTES
Springer-Verlag New York, Inc., 1983
Residue Reviews, Volume 87, pp 43-90

16. ABSTRACT

The use of behavioral endpoints in environmental hazard and impact assessment has become a major field of study in recent years. Although behavior has always been accepted as an important aspect of animal survival and ecology, toxicological research over the past two decades has concentrated primarily on lethality, growth, and reproductive success. Behavioral toxicology has lagged in areas of impact assessment for several reasons: (1) difficulties in objectively quantifying behavioral endpoints, (2) variability associated with the endpoint, (3) lack of standardized testing procedures which would provide more comparable data, and (5) difficulties in extrapolating to field situations the ecological significance of effects observed in the laboratory. These problems certainly are not unique to ethological testing but have proven to be obstacles to its success as an impact assessment tool.

In this review we discuss a broad range of chemical contaminants by comparing concentrations causing preference and/or avoidance with concentrations acute and chronic toxicity. Although previous reviews have been presented on various aspects of behavioral responses of fishes and invertebrates to aquatic contaminants (Anderson 1971, Sutterlin 1974, Schere 1977, Maciorowski et al, 1977, Larrik et al. 1978, Cherry and Cairns 1982, Cairns and van der Schalie 1981), no review to date has been found which systematically evaluates the relative sensitivities of the diverse testing methods.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	unclassified	49
	20. SECURITY CLASS *(This page)*	22. PRICE
	unclassified	

EPA Form 2220-1 (9-73)

EPA-600/J-83-022
JOURNAL ARTICLE

A review of the preference-avoidance responses of fishes to aquatic contaminants

By

J.D. GIATTINA* AND R.R. GARTON*

Contents

I. Introduction 44
II. Methods and definition of terms 44
III. Metals 46
a) Copper 47
b) Zinc 52
c) Mercury 53
d) Cadmium 53
e) Nickel 56
f) Lead 57
IV. Organochlorine compounds 57
a) DDT 60
b) PCBs 61
c) 2,4-D 63
V. Organophosphates 64
a) Malathion 65
b) Fenitrothion 66
c) Parathion 67
VI. Miscellaneous compounds 68
a) Phenol 68
b) Pulp and paper mill effluents 68
c) Chlorine and chlorinated effluents 72
Summary 75
References 78

*U.S. Environmental Protection Agency, Corvallis Environmental Research Laboratory, 200 S.W. 35th Street, Corvallis, OR 97333.

© 1983 by Springer-Verlag New York, Inc.
Residue Reviews, Volume 87.
pp 43-90

I. Introduction

The use of behavioral endpoints in environmental hazard and impact assessment has become a major field of study in recent years. Although behavior has always been accepted as an important aspect of animal survival and ecology, toxicological research over the past two decades has concentrated primarily on lethality, growth, and reproductive success. Behavioral toxicology has lagged in areas of impact assessment for several reasons: (1) difficulties in objectively quantifying behavioral endpoints, (2) variability associated with the endpoint, (3) lack of standardized testing procedures which would provide more comparable data, and (4) difficulties in extrapolating to field situations the ecological significance of effects observed in the laboratory. These problems certainly are not unique to ethological testing but have proven to be obstacles to its success as an impact assessment tool.

As an assessment tool, the study of behavior must be limited to those observations which can be objectively and rapidly quantified. These criteria effectively reduce the infinite range of behaviors for study, so that behavioral bioassays for aquatic organisms have developed along four principal lines of inquiry: (1) locomotor responses, primarily preference-avoidance reactions and activity changes; (2) ventilatory responses, primarily opercular movements and coughs; (3) predator-prey interactions; and (4) toxicant-induced changes in conditioned behavior. Although a myriad of behavioral patterns are essential to the survival of a species, we chose to focus on the preference-avoidance reactions in this review because of the apparent ecological and economic significance of this behavior. Effective concentrations are reported for the other three categories, however, when these data are available. For a complete review of behavioral toxicology in fishes, as measured by changes in conditioned responses, see Marcucella and Abramson (1978).

In this review we discuss a broad range of chemical contaminants by comparing concentrations causing preference and/or avoidance with concentrations eliciting other behavioral changes, biochemical or physiological alterations, and acute and chronic toxicity. Although previous reviews have been presented on various aspects of behavioral responses of fishes and invertebrates to aquatic contaminants (Anderson 1971, Sutterlin 1974, Scherer 1977, Maciorowski *et al.* 1977, Larrick *et al.* 1978, Cherry and Cairns 1982, Cairns and van der Schalie 1981), no review to date has been found which systematically evaluates the relative sensitivities of the diverse testing methods.

II. Methods and definitions of terms

A wide variety of experimental techniques, ranging from highly automated computer-interfaced systems to those using human observation, have been used to quantify behavioral responses. For preference-avoidance reactions, the experimental chambers generally fall into two categories: (1) steep-gradient chambers provide the organism with distinct choices between water treated to a given con-

centration and untreated water, and (2) shallow-gradient chambers provide a toxicant gradient so that the organism can be exposed to a range of concentrations over a given distance (Fig. 1).

Generally, three criteria are measured to determine preference or avoidance responses: (1) time spent in the test water, (2) the number of entries into the test water, and (3) the distribution of fish in relation to the test water after a given time interval. A more complete breakdown of an organism's behavior is possible depending upon the sophistication of the experimental apparatus. Kleerekoper *et al.* (1972), for example, using a computer-interfaced system, considered eight

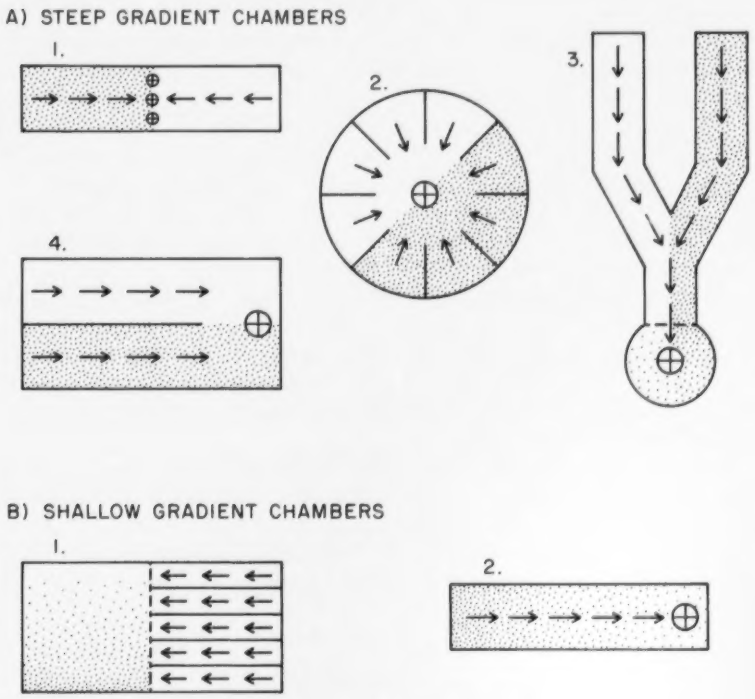

Fig. 1. Schematic diagram of several of the more common systems used to test for locomotor resonses of fishes to aquatic contaminants:
A. Steep gradient chambers–1. counter-current flow chamber (Cherry *et al.* 1977 a and b, 1979, 1982, Giattina *et al.* 1981 and 1982, Sprague 1964 a and 1968, Sprague and Drury 1969). 2. "rosette" apparatus (Kleerekoper *et al.* 1973). 3. "Y" trough (Hansen, 1969, Hansen *et al.* 1973 a and b, 1974, Kynard 1974). 4. modified fluvarium (Black and Birge 1980).
B. Shallow gradient chamber–1. fluvarium (Hansen 1972). 2. linear gradient (Ishio 1965, Cripe *et al.* 1975, Cripe 1979).

locomotor characteristics in determining the response of goldfish (*Carrassius auratus*) to a shallow gradient of copper. Most studies, however, are limited in the number of parameters they consider because they depend solely on human observation. Activity changes have also been commonly measured, particularly in early warning devices designed for in-plant monitoring of effluents (Shirer *et al.* 1968, Waller and Cairns 1972, Hall *et al.* 1975, see also Meffert 1968 and Scherer *et al.* 1979).

Very often concentrations effective at causing avoidance (or preference) responses are reported as "threshold" concentrations. This term, however, is given different definitions by various authors, leading to a disparity in reported concentrations which, to some extent, may be artificial. Many authors define threshold as the first concentration tested causing a statistically significant change (preference or avoidance) from control behavior. This change can be measured using the criteria noted earlier. Others prefer to define the threshold as that concentration below which no effects can be observed. This threshold can be a concentration actually tested at which no effect was observed, or it can be extrapolated assuming a linear dose-response relationship. For this review, we prefer the former definition, so that when the term threshold is used it implies statistical significance. The variety of other terms used to characterize toxicological responses of fishes to aquatic contaminants will be defined as necessary.

The range of experimental methods has, no doubt, contributed significantly to variations in the observed behavioral endpoints, often making comparisons difficult, as well as questionable. We feel, however, that preference-avoidance testing has reached a point where, at least, broad generalizations and summaries are needed to define future research needs and to provide useful information to those working in environmental impact assessment.

Although many observations concerning the behavioral effects of toxicants are anecdotal, we have limited our discussion, for the most part, to studies directly quantifying behavioral endpoints. For clarity the biological effects of the toxicants reviewed here are presented individually under broad categories based on chemical types, concluding with a summary of the general relationships noted from this review.

III. Metals

The term "heavy metals," although commonly used, is a poorly defined classification covering a broad array of elements which differ in their chemical and biological properties (Neiboer and Richardson 1980). Characterizations and comparisons of the responses of aquatic organisms to metals is further complicated by the many metal-ligand complexes formed and the changing ionic composition of a metal solution given different water qualities. The relationship between metal toxicity and water hardness has been documented for several metals (Andrew *et al.* 1976, Bryan 1976, McCrady and Chapman 1979, Calamari *et al.*

1980, Freedman *et al.* 1980). In most of the behavioral and toxicological literature, however, effects have been related to total recoverable metal concentrations with little or no distinction between metal forms. For this reason, concentrations referred to in this review are in terms of total metal unless otherwise stated; we acknowledge, however, that metal form may be a considerable source of variation when comparisons are made between studies with concomitant changes in water quality.

Copper, zinc, mercury, cadmium, nickel, and lead have been the most extensively studied metals in relation to their organismic effects; hence, we focus on these in the following discussion.

a) Copper

1. Preference-avoidance responses.–Copper (Cu) avoidance concentrations vary depending on the species and the test conditions used (Table I). The majority of Cu preference-avoidance research has been conducted on salmonids, and avoidance concentrations range from 0.1 (Folmar 1976) to 70 μg/L (Black and Birge 1980). A variety of factors have been shown to influence or alter avoidance responses to Cu. For example, goldfish (*Carassius auratus*) exposed to Cu in a shallow gradient displayed preference reactions, whereas exposure to the same concentrations in a steep gradient resulted in avoidance (Kleerekoper *et al.* 1972, Timms *et al.* 1972, Westlake *et al.* 1974). The importance of gradient steepness, or the rate of change in toxicant concentration from one location to another, was also recognized by Ishio (1965). In addition to this observation, however, evidence indicates that the Cu concentration *per se* has also led to variable responses in both fishes and invertebrates. Organisms may avoid low concentrations of Cu only to be attracted to higher concentrations (Black and Birge 1980, Giattina *et al.* 1982, Maciorowski *et al.* 1977). Two hypotheses have been proposed to explain this ambivalent behavior, which has been noted for other chemicals as well: (1) the attraction observed at higher concentrations is a pseudo-preference response caused by chemically induced narcosis (Jones 1947 and 1948), and/or (2) initial avoidance followed by attraction may be caused by changes in the sensitivity of the chemoreceptors at varying concentrations (Costa 1966, Hara *et al.* 1976, Sprague and Drury 1969). Neither hypothesis, however, satisfactorily explains this behavior at present.

The preference-avoidance response of goldfish to Cu was also shown to be influenced by temperature. Given a choice between 10 μg/L Cu and clean water, goldfish avoided the Cu solution; however, when the water temperature was raised 0.4°C (21.1 to 21.5°C) in the Cu zone, goldfish were attracted to this area significantly more so than when temperature attraction occurred without Cu present (Kleerekoper *et al.* 1973).

Copper is one of the few elements for which avoidance behavior has been documented under field conditions. Sprague *et al.* (1965) and Saunders and Sprague (1967) reported that equitoxic Cu and zinc mixtures above 38 and 480

Table I. *Total copper concentrations (arranged in increasing order) causing avoidance responses and toxicological effects as reported for a variety of species and testing procedures.*

Effect	Concentration (μg/L)	Hardness (mg/L)	Species	Citation
Avoidance	0.1	89.5	*Salmo gairdneri* (rainbow trout)	Folmar (1976)
Avoidance	2.4	20	*S. salar* (Atlantic salmon)	Sprague *et al.* (1965)
Avoidance	5.0	5.4	*Carassius auratus* (goldfish)	Westlake *et al.* (1974)
Avoidance	6.4	23-27	*S. gairdneri* (rainbow trout)	Giattina *et al.* (1982)
MATC[a]	9.5-17.4	45.4	*Salvelinus fontinalis* (brook trout)	McKim & Benoit (1971)
No effect	10-15	45.4	*S. gairdneri* (rainbow trout)	McKim *et al.* (1978)
96-hr LC_{50}	17	24	*S. gairdneri* (rainbow trout)	Chapman (1978)
96-hr LC_{50}	18	20-30	*Ptychocheilus oregonensis* (northern squawfish)	Andros & Garton (1980)
96-hr LC_{50}	19	24	*Oncorhynchus tshawytscha* (coho salmon)	Chapman (1978)
Chronic value	19	45.4	*S. gairdneri* (rainbow trout)	McKim *et al.* (1978)

Reproductive impairment (3-week exposure)	22	45.3	*Daphnia magna*	Biesinger & Christensen (1972)
Incipient lethal level	48	20	*S. salar* (Atlantic salmon)	Sprague (1964 b)
Avoidance	50	---	*Coregonus clupeaformis* (lake whitefish)	Hara & Scherer as reported by Maciorowski *et al.* (1977)
Avoidance	70	112.4	*S. gairdneri* (rainbow trout)	Black & Birge (1980)

[a] Maximum Acceptable Toxicant Concentration.

μg/L, respectively, appeared to prevent upstream migration of Atlantic salmon (*Salmo salar*) parr. This species was also shown to avoid 44 μg/L Cu in outdoor gradient tests (Sutterlin and Gray 1973). Geckler *et al.* (1976), conducting a field study on Shayler Run in Ohio, added Cu to the stream for 33 mon at a concentration of approximately 120 μg/L. A variety of warmwater fishes were found to avoid the higher concentrations of Cu (77 to 120 μg/L), in some cases choosing the lowest concentrations available for spawning. As a result, Geckler *et al.* concluded that laboratory chronic tests underestimated instream toxicity by about two times because avoidance, although having had a significant effect in the stream, was generally not considered in the laboratory toxicity tests.

Thus, based on the limited data available, avoidance behavior in response to Cu appears to be an ecologically significant factor which can influence fish distribution and movement under natural conditions. Laboratory preference-avoidance tests with Cu, however, appear to underestimate concentrations causing field avoidance. This conclusion, although not surprising considering the many environmental influences and appetitive behaviors which affect field responses, should be substantiated with additional field research.

2. Behavioral, physiological, and biochemical responses.—Copper avoidance thresholds were found to be among the most sensitive indicators of sublethal stress when compared to other behavioral and biochemical assays. For example, Drummond *et al.* (1973) reported that cough frequency in brook trout (*Salvelinus fontinalis*) increased significantly after a four-hr exposure to Cu from 6 to 15 μg/L; however, Sellers *et al.* (1975) found that Cu alone did not appreciably increase coughing frequency in the rainbow trout (*Salmo gairdneri*) over the range of 20 to 90 μg/L. Waiwood and Beamish (1978) found reduced critical swimming speeds in rainbow trout at 10 μg/L Cu depending on hardness, pH, and time of exposure. Coho salmon (*Oncorhynchus kisutch*) had temporary increases in cortisol levels after a 2-hr exposure to 15 μg/L Cu (Schreck and Lorz 1978); concentrations of 38 to 39 and 67 to 69 μg/L caused significant increases in red blood cell count, hematocrit, hemoglobin, plasma glutamic oxalacetic transaminase (GOT), and total protein in brook trout after 6 and 21 days of exposure, respectively (McKim *et al.* 1970). Hara (1972) reported that 100 μg/L Cu blocked olfactory responses of coho and sockeye salmon (*O. nerka*) after a 12-hr exposure, and postulated that this blocking effect was caused by cupric ion interference with either receptor sites or with enzymatic components of the receptor membranes.

3. Acute and chronic toxicity responses.—Sublethal behavioral effects caused by Cu were observed at concentrations generally equal to or less than those concentrations causing acute or chronic toxicity, particularly for the salmonids (Table I). Chronic concentrations for this family ranged from 10 to 48 μg/L and, although salmonids avoided concentrations from 0.1 to 70 μg/L, most studies reported Cu avoidance at less than 10 μg/L.

Table II. *Total zinc concentrations (arranged in increasing order) as reported for a variety of species and testing procedures.*

Effect	Concentration (μg/L)	Hardness (mg/L)	Species	Citation
Avoidance	5.6	13-15	*Salmo gairdneri* (rainbow trout)	Sprague (1968)
Chronic value	47	104	*Daphnia magna*	Chapman *et al.* (as reported by USEPA 1980 a)
Chronic value	47	44	*Jordanella floridae* (flagfish)	Spehar (1976)
Avoidance	50	112.4	*S. gairdneri* (rainbow trout)	Black & Birge (1980)
Avoidance	54	20	*S. salar* (Atlantic salmon)	Sprague (1964 a)
Reproductive impairment (3-week exposure)	70	13-15	*D. magna*	Biesinger & Christensen (1972)
96-hr LC_{50}	93	24	*S. gairdneri* (rainbow trout)	Chapman (1978)
96-hr LC_{50}	97	25	*Oncorhynchus tshawytscha* (coho salmon)	Chapman (1978)
Chronic value	106	46	*Pimephales promelas* (fathead minnow)	Benoit & Holcombe (1978)
Chronic value	277	26	*S. gairdneri* (rainbow trout)	Sinley *et al.* (1974)
Incipient lethal	600	20	*S. salar* (Atlantic salmon)	Sprague (1964 b)

b) Zinc

1. Preference-avoidance responses.—Zinc (Zn) avoidance thresholds were also widely variable depending upon species and test conditions (Table II). An additional source of variation between species, however, was noted: that is, basic differences in the control behavior of the species being compared could lead to observable differences in avoidance behavior. Sprague (1968) attributed the approximate 10-fold difference in zinc avoidance thresholds he reported for rainbow trout (5.6 μg/L) and Atlantic salmon (54 μg/L, Sprague 1964 a) to basic behavioral differences of this sort. Young salmon tended to be more sedentary and unaware of choices in water quality, hence less responsive; rainbow trout, on the other hand, were more active enabling them to discern quickly the presence of polluted water.

The only documentation of field avoidance to Zn was noted earlier in conjunction with Cu avoidance. Field concentrations of Cu (17 to 21 μg/L) and Zn (210 to 258 μg/L) caused downstream movements of Atlantic salmon, while equitoxic Cu and Zn mixtures above 38 and 480 μg/L, respectively, prevented upstream migrations (Sprague *et al.* 1965, see also Saunders and Sprague 1967). In laboratory avoidance tests, the two metals acting together showed a statistically significant potentiation compared to the action of Zn alone (Sprague 1964 a). Again, the higher field avoidance thresholds were most likely caused by the strong motivation for this migratory species to move upstream, a condition not reproduced in laboratory tests (Sprague *et al.* 1965).

2. Behavioral, physiological, and biochemical responses.—In comparison with other test methods and biological endpoints, avoidance responses were among the most sensitive indicators of sublethal Zn stress. Sellers *et al.* (1975) reported a slight increase in ventilation frequency of rainbow trout at 20 μg/L Zn, and an increase in cough frequency at 150 μg/L. This agrees with Cairns *et al.* (1982) who found a significant increase in the ventilation frequency of steelhead trout (*S. gairdneri*) at a zinc concentration of 144 μg/L (12 C; 25 mg/L hardness). Bluegill sunfish (*Lepomis macrochirus*) became hyperactive after initial exposures to 100 and 5,000 μg/L Zn (Ellgaard *et al.* 1978), showed significant changes in movement patterns in the range of 2,940 to 3,640 μg/L Zn (Waller and Cairns 1972), and increased their breathing rate in the range of 2,550 to 8,700 μg/L Zn (Sparks *et al.* 1972). Rainbow trout also exhibited a decrease in blood pO_2 after a 9-hr exposure and an increase in blood pH immediately after exposure to 1,430 μg/L Zn (Sellers *et al.* 1975).

3. Acute and chronic toxicity responses.—Zinc avoidance thresholds for salmonids were generally equal to or below most chronic values reported in the literature (Table II). The invertebrate, *Daphnia magna*, and the flagfish (*Jordanella floridae*) appear to be the most sensitive aquatic organisms tested, each with a chronic value of 47 μg/L Zn (Chapman *et al.* as reported by USEPA 1980 a and Spehar 1976, respectively). The Zn avoidance thresholds reported for the salmonids ranged from 54 μg/L for Atlantic salmon (Sprague 1964 a) to 5.6 μg/L for rainbow trout (Sprague 1968). Black and Birge (1980) also reported a Zn

avoidance threshold of 50 μg/L for rainbow trout; both thresholds, however, are well below the chronic value of 277 μg/L Zn for rainbow trout given by Sinley *et al.* (1974) at a water hardness of 26 mg/L.

c) Mercury

1. Preference-avoidance responses.—Relatively few behavioral data were available for mercury (Hg) (Table III); the majority of studies have focused on toxicity, bioconcentration, and biomagnification of organic Hg by aquatic organisms, with the related potential for harm to human beings. Rainbow trout behavior, however, was a sensitive indicator of the presence of Hg, but, unlike Cu and Zn stress which caused avoidance, trout were observed to be significantly attracted to Hg at 0.2 μg/L (Black and Birge 1980). Locomotor responses at very low Hg levels could, then, increase the chances of bioconcentration and biomagnification by bringing fishes into contact with apparently harmless concentrations.

2. Behavioral, physiological, and biochemical responses.—The preference behavior of rainbow trout for 0.2 μg/L Hg noted above (Black and Birge 1980) was the most sensitive organismic effect recorded. Drummond *et al.* (1974) found that methylmercuric chloride and mercuric chloride both caused a significant increase in the cough frequency of brook trout at 3 μg/L Hg, and mosquitofish (*Gambusia affinis*) showed a decreased ability to avoid predation after a 24-hr exposure to 10 μg/L Hg as mercuric chloride (Kania and O'Hara 1974). An impairment of the conditioned avoidance response by goldfish was noted at 3 μg/L Hg (Weir and Hine 1970). The roach (*Leuciscus rutilus*) also exhibited a significant decrease in the critical r.p.m. (reduced ability to remain upright in a rotating mass of water) after exposure to 5 μg/L Hg as methylmercuric hydroxide for 10 days (Lindahl and Schwanbom 1971). Gill tissue excised from the striped bass (*Morone saxatilis*) showed a decrease in oxygen consumption after a 30-day exposure to 5 μg/L Hg (Dawson *et al.* 1977), and Hara (1972) found that 100 μg/L Hg reduced olfactory responses 10 to 40% in coho and sockeye salmon after a 3-day exposure.

3. Acute and chronic toxicity responses.—Methylmercury is the most toxic Hg form. The lowest chronic value reported was 0.5 μg/L methylmercury for brook trout (McKim *et al.* 1976), compared with a chronic value of 1.27 μg/L of mercuric chloride for *Daphnia magna* (Biesinger *et al.* as reported by USEPA 1980 b). Bioconcentration of Hg in brook trout has been shown to occur at water concentrations down to 0.03 μg/L (McKim *et al.* 1976). Ninety-six hr LC_{50}'s generally ranged from 65 μg/L methyl mercuric chloride for brook trout (McKim *et al.* 1976) to 220 μg/L mercuric chloride for rainbow trout (Macleod and Pessah 1973).

d) Cadmium

1. Preference-avoidance responses.—The only avoidance threshold reported for cadmium (Cd) was 50 μg/L for rainbow trout by Black and Birge (1980) (Table IV).

2. Behavioral, physiological, and biochemical responses.—A concentration of 0.1 μg/L Cd caused alterations in the normal spawning behavior (courting, aggres-

Table III. *Total mercury concentrations (arranged in increasing order) causing avoidance responses and toxicological effects as reported for a variety of species and testing procedures.*

Effect	Concentration (μg/L)	Hardness (mg/L)	Species	Citation
Attraction (mercuric chloride)	0.2	112.4	*Salmo gairdneri* (rainbow trout)	Black & Birge (1980)
Chronic value (methylmercuric chloride)	0.52	---	*Salvelinus fontinalis* (brook trout)	McKim *et al.* (1976)
Chronic value (mercuric chloride)	1.27	---	*Daphnia magna*	Biesinger *et al.* (as reported by USEPA 1980 b)
Impaired conditioned avoidance response (mercuric chloride)	3	---	*Carassius auratus* (goldfish)	Weir & Hein (1970)
96-hr LC_{50} (methylmercuric chloride)	65	---	*S. fontinalis* (brook trout)	McKim *et al.* (1976)
96-hr LC_{50} (mercuric chloride)	220	---	*S. gairdneri* (rainbow trout)	Macleod & Pessah (1973)
Avoidance	40,700	---	*Pygosteus pungitius* (ten-spine stickleback)	Jones (1947)

Table IV. *Total cadmium concentrations (arranged in increasing order) causing avoidance responses and toxicological effects as reported for a variety of species and testing procedures.*

Effect	Concentration (μg/L)	Hardness (mg/L)	Species	Citation
Chronic value	0.15	53	*Daphnia magna*	Chapman *et al.* (as reported by USEPA 1980 c)
200-hr LC_{10}	0.7	24	*Salmo gairdneri* (rainbow trout)	Chapman (1978)
96-hr LC_{50}	1.0	24	*S. gairdneri* (rainbow trout)	Chapman (1978)
Chronic value	1.7	36	*Salvelinus fontinalis* (brook trout)	Sauter *et al.* (1976)
96-hr LC_{50}	1.8	23	*Oncorhynchus kisutch* (coho salmon)	Chapman (1978)
Chronic value	9.2	187	*S. fontinalis* (brook trout)	Sauter *et al.* (1976)
MATC[a]	37-57	201	*Pimephales promelas* (fathead minnow)	Pickering & Gast (1972)
Avoidance	50	112.4	*S. gairdneri* (rainbow trout)	Black & Birge (1980)

[a] Maximum Acceptable Toxicant Concentration.

sive territoriality, and female acceptance of males) of flagfish during chronic toxicity tests (Spehar *et al.* 1978), and Benoit *et al.* (1976) noted a similar inability of brook trout to spawn at 3.4 μg/L Cd because of hyperactive behavior. Also, fathead minnow (*Pimephales promelas*) vulnerability to predation increased after a 21-day exposure to 2.5 μg/L Cd (Sullivan *et al.* 1978). The maximum acceptable toxicant concentration (MATC) previously determined for the fathead minnow was between 37 and 57 μg/L Cd (Pickering and Gast 1972).

Dawson *et al.* (1977) reported a decrease in the gill-tissue oxygen consumption of striped bass following a 30-day exposure at 0.5 μg/L Cd. In general, however, cadmium-induced biochemical and physiological changes occurred at higher concentrations. For example, Bengtsson *et al.* (1975) noted vertebral fractures in the minnow (*Phoxinus phoxinus*) at 7.5 μg/L Cd, and Roch and Maly (1979) found that 300 μg/L Cd caused hypocalcemia in rainbow trout. A concentration of 100 μg/L caused changes of blood plasma electrolyte (potassium, calcium, and magnesium) concentrations in flounder (*Pleuronectes flesus*) exposed for 15 days (Larsson *et al.* 1976), and concentrations greater than 1,000 μg/L Cd were required to inhibit liver catalase activity in the mummichog (*Fundulus heteroclitus*) (Pruell and Engelhardt 1980).

3. Acute and chronic toxicity responses.—The cladoceran, *Daphnia magna*, and the brook trout were the most sensitive species tested, in terms of chronic toxicity, with chronic value ranges of 0.15 to 0.44 μg/L Cd (Chapman *et al.* as reported by USEPA 1980 c) and 1.7 to 9.2 μg/L Cd (Sauter *et al.* 1976), respectively, depending on water hardness. Benoit *et al.* (1976) estimated the MATC for brook trout to be between 1.7 and 3.4 μg/L Cd and the MATC for the fathead minnow was between 37 and 57 μg/L Cd (Pickering and Gast 1972) (Table IV). Eaton *et al.* (1978) reported that seven species of freshwater fish were killed or their growth was retarded by Cd concentrations ranging from 4 to 12 μg/L (hardness = 45 mg/L as $CaCO_3$).

e) Nickel

1. Preference-avoidance responses.—The only behavioral effect recorded for nickel (Ni) was avoidance by rainbow trout at 23.9 μg/L Ni at a hardness ranging from 24 to 29 mg/L as $CaCO_3$ (Giattina *et al.* 1982) (Table V).

2. Behavioral, physiological, and biochemical responses.—Becker and Wolford (1980), using the critical thermal maximum procedure, found that 1,500 μg/L Ni significantly suppressed the resistance of rainbow trout to elevated temperatures after 7 to 21 days exposure. Also, Christensen (1972) reported that 2,000 mg/L Ni were needed to cause approximately 17 and 20% inhibition in the *in vitro* activity of plasma lactic dehydrogenase (LDH) and plasma GOT of the white sucker (*Catostomus commersoni*), respectively.

3. Acute and chronic toxicity responses.—Nebeker *et al.* (1982) reported a chronic value of 350 μg/L Ni for rainbow trout, which was well above the avoid-

ance threshold reported by Giattina *et al.* (1982). Chronic values for other species ranged from 14.8 μg/L for *Daphnia magna* (Chapman *et al.* as reported by USEPA 1980 d) to 527 μg/L for the fathead minnow (Pickering 1974) (Table V). Acute values (96-hr. LC_{50}'s) were generally at least an order of magnitude greater (Table V).

f) Lead

1. **Preference-avoidance responses.**—No lead (Pb) behavioral thresholds have been reported in the literature for salmonids. Preliminary tests in our laboratory, however, indicate that rainbow trout will avoid Pb at approximately 26 μg/L (hardness = 26 to 31 mg/L as $CaCO_3$) using the avoidance system described in Giattina *et al.* (1982). Avoidance thresholds for two warmwater fish species, the minnow, *Phoxinus phoxinus*, and the three-spine stickleback, *Gasterosteus aculeatus* (Jones 1948), and one invertebrate, *Gammarus pulex* (Costa 1966), were well above chronic toxicity values reported in the literature (Table VI). Summerfelt and Lewis (1967) found that green sunfish (*Lepomis cyanellus*) would not avoid Pb at 10, 20, or 40 mg/L.

2. **Behavioral, physiological, and biochemical responses.**—Weir and Hine (1970) reported impairment of the conditioned avoidance response in goldfish after exposure to 70 μg/L. Biochemical effects, however, have been observed in salmonids at much lower Pb concentrations. For example, Hodson *et al.* (1978) found that rainbow trout exposed to 13 μg/L Pb for at least one wk had significant increases in red blood cells (RBC), decreases in RBC volume and RBC iron content, and decreases in RBC δ-amino levulinic acid dehydratase (ALA-D) activity. Decreased ALA-D activity was also noted at 10 and 90 μg/L Pb in rainbow and brook trout, respectively (Hodson *et al.* 1977). Christensen *et al.* (1977) reported decreased hemoglobin content and inhibition of GOT activity in brook trout following a 56-day exposure to 58 μg/L Pb.

3. **Acute and chronic toxicity responses.**—Lead chronic values generally range from 5.6 μg/L for rainbow trout (Davies *et al.* 1976) to 92 μg/L for bluegill sunfish (Sauter *et al.* 1976). Ninety-six hr LC_{50}'s for these same species were 1,170 (Davies *et al.* 1976) and 23,800 μg/L Pb (Pickering and Henderson 1966), respectively (see Table VI). The avoidance threshold appears to fall in between chronic and acute toxic levels for rainbow trout.

IV. Organochlorine compounds

This category includes a broad array of organic biocides and industrial chemicals, the best known being DDT [1,1,1-trichloro-2,2-bis(*p*-chlorophenyl)-ethane] and the polychlorinated biphenyls (PCBs) because of their persistent and ubiquitous nature. Despite the enormous public attention these chemicals have received over the past two decades, relatively few data are available that describe their chronic effects on aquatic organisms. Most studies have concentrated on the acute

Table V. *Total nickel concentrations (arranged in increasing order) causing avoidance responses and toxicological effects as reported for a variety of species and testing procedures.*

Effect	Concentration (μg/L)	Hardness (mg/L)	Species	Citation
Chronic value	14.8	51	*Daphnia magna*	Chapman *et al.* (as reported by USEPA 1980 d)
Avoidance	23.9	24-29	*Salmo gairdneri* (rainbow trout)	Giattina *et al.* (1982)
Chronic value	350	50	*S. gairdneri* (rainbow trout)	Nebeker *et al.* (1982)
Chronic value	527	210	*Pimephales promelas* (fathead minnow)	Pickering (1974)
96-hr LC_{50}	645	54	*D. magna*	Chapman *et al.* (as reported by USEPA 1980 d)
96-hr LC_{50}	4,580	20	*P. promelas* (fathead minnow)	Pickering & Henderson (1966)
96-hr LC_{50}	35,500	---	*S. gairdneri* (rainbow trout)	Hale 1977

Table VI. *Total lead concentrations (arranged in increasing order) causing avoidance responses and toxicological effects as reported for a variety of species and testing procedures.*

Effect	Concentration (μg/L)	Hardness (mg/L)	Species	Citation
Chronic value	5.6[a]	28	*Salmo gairdneri* (rainbow trout)	Davies *et al.* (1976)
Chronic value	12	52	*Daphnia magna*	Chapman *et al.* (as reported by USEPA 1980 e)
Chronic value	24[a]	353	*S. gairdneri* (rainbow trout)	Davies *et al.* (1976)
Avoidance	26	26-31	*S. gairdneri* (rainbow trout)	Giattina & Garton (unpublished data)
Chronic value	57[a]	44	*Salvelinus fontinalis* (brook trout)	Holcombe *et al.* (1976)
Impaired conditioned avoidance response	70	50	*Carassius auratus* (goldfish)	Weir & Hine (1970)
Chronic value	92	41	*Lepomis macrochirus* (bluegill sunfish)	Sauter *et al.* (1976)
Avoidance	400	---	*Phoxinus phoxinus*	Jones (1948)
96-hr LC_{50}	1,170	28	*S. gairdneri* (rainbow trout)	Davies *et al.* (1976)
Avoidance	2,000	---	*Gasterosteus aculeatus* (three-spine stickleback)	Jones (1948)
96-hr LC_{50}	23,800	20	*L. macrochirus* (bluegill sunfish)	Pickering & Henderson (1966)

[a] Measured as dissolved lead as opposed to total lead.

toxicity and the bioconcentration of these compounds due to their high lipid solubility. Agricultural use of DDT was banned in 1972 by the EPA; however, this pesticide is still used in some other countries. Production of PCBs in the United States ceased as of 1980.

We will focus on the organismic effects of DDT and the PCBs, in addition to derivatives of the phenoxycarboxylic acid herbicide 2,4-D [(2,4-dichlorophenoxy) acetic acid]. Livingston (1977) has reviewed the literature concerning the acute and the chronic effects of pesticides on aquatic organisms.

a) DDT

1. Preference-avoidance responses.—The most sensitive DDT avoidance response noted was for the sheepshead minnow (*Cyprinodon variegatus*), a marine species, which avoided concentrations in the range of 5 to 50 μg/L but showed no significant response to 100 μg/L (Hansen 1969). Mosquitofish avoided 100 μg/L DDT (Hansen *et al.* 1973 a), but showed changes in salinity preference induced by lower concentrations of 5, 10, and 20 μg/L (Hansen 1972). Kynard (1974) tested both DDT-susceptible and DDT-resistant mosquitofish, also in a Y-maze similar to Hansen's, but found that significant avoidance did not occur until 10,000 μg/L with susceptible fish and no avoidance occurred with resistant organisms.

2. Behavioral, physiological, and biochemical responses.—A common behavior measured following DDT exposure was the change in selected temperature of a species. Atlantic salmon, for example, had a biphasic response to 24-hr DDT exposures: when acclimated at 17°C, a low concentration (5 μg/L) caused a 2°C reduction in the selected temperature of salmon, whereas at higher concentrations (10 to 50 μg/L), the selected temperature increased by as much as 8°C (Ogilvie and Anderson 1965). These results were later confirmed and shown to persist for a month after exposure to 50 μg/L DDT (Ogilvie and Miller 1976). A similar response was noted for brook trout, which selected lower temperatures following a 24-hr exposure to 10 μg/L DDT, but increased the selected temperature after exposure to 50 μg/L (Miller and Ogilvie 1975). An upward shift in the selected temperature of brook trout exposed to 100 μg/L was also reported by Peterson (1973). Methoxychlor [2,2-bis-(*p*-methoxy-phenyl)-1,1,1-trichloroethane], a DDT analog, at 20 and 30 μg/L caused brook trout to select lower temperatures, but recovery to control values occurred after 5 days (Gardner 1973).

DDT exposure (5 to 100 μg/L) of Atlantic salmon eggs from gastrulation to hatching delayed, and in some cases, obliterated the appearance of normal posturing and locomotor behaviors by alevins (Dill and Saunders 1974). Schaumberg *et al.* (1967) reported increased cough frequencies by coho salmon at 5 and 20 μg/L following 5- and 3-day exposures, respectively, and rainbow trout showed significant increases in cough frequencies almost immediately following exposure to DDT with the threshold concentration estimated between 52 and 140 μg/L (Lunn *et al.* 1976). Goldfish did not exhibit changes in general exploratory behavior; however, subtle changes were evident after exposure to 10 μg/L DDT

for 4 days (Davy *et al.* 1973). A 24-hr exposure of Atlantic salmon to 70 μg/L DDT had no apparent effect on this species' ability to avoid brook trout predation (Hatfield and Anderson 1972).

Conditioning experiments were commonly used to elucidate the possible effects of DDT on learning ability. For example, Davy *et al.* (1972) found that a 4-day exposure of goldfish to 10 μg/L DDT caused a reduction in the short-term retention or "memory" process involved in the exploratory behavior of this species, and Anderson and Prins (1970) reported that a 24-hr exposure of brook trout to 20 μg/L decreased the ability of trout to learn the propeller-tail reflex. Brook trout reportedly failed to acquire a conditioned avoidance response after a 24-hr exposure to 20 μg/L DDT (Anderson and Peterson 1969). This result was later negated in experiments by Jackson *et al.* (1970), who demonstrated that brook trout could be conditioned in a chamber modified from the one used by Anderson and Peterson. Atlantic salmon exposed to 7 μg/L DDT for 24 hr exhibited no effect on their ability to learn a conditioned avoidance response; in fact, at 70 μg/L, salmon learned significantly faster than controls (Hatfield and Johansen 1972).

In general, 5 μg/L was the lowest DDT concentration in water which had a significant effect on behaviors such as cough frequency, temperature selection, and avoidance. Ellgaard *et al.* (1977), however, reported DDT-induced hyperactivity of bluegills at concentrations as low as 0.008 μg/L after a 3 to 4 day exposure. This value was well below all other DDT behavioral thresholds.

Christensen and Reidel (1981) found that approximately 106 mg/L DDT were required to cause 50% inhibition of lipase activity *in vitro*, and estimated 7 mg/L as the threshold concentration causing 1% lipase inhibition. Moffett and Yarbrough (1972), however, reported succinic dehydrogenase activity inhibition in mosquitofish at approximately 4 μg/L after a 40-min exposure. Also, Mg^{2+}ATPase inhibition in the fathead minnow occurred at 0.5 μg/L DDT after 266 days (Desaiah *et al.* 1975). Anderson (1968) also reported that exposure to DDT from 100 to 300 μg/L for 24 hr caused the lateral line nerve of brook trout to be hypersensitive to stimulation.

3. Acute and chronic toxicity responses.—Post and Schroeder (1971) reported a 96-hr LC_{50} of 1.7 μg/L DDT for rainbow trout but no chronic values have been reported for this species. Fathead minnows exposed to DDT in water and diet exhibited a MATC of approximately 0.40 μg/L DDT, and in the same study a 96-hr LC_{50} of 48 μg/L was reported for this species (Jarvinen *et al.* 1977).

b) PCBs

1. Preference-avoidance responses.—Again, relatively few data were available on the behavioral effects of PCBs on aquatic organisms. Hansen *et al.* (1974) found that mosquitofish were capable of avoiding 0.1, 1.0, and 10 mg/L of Aroclor 1254. Grass shrimp (*Palaemonetes pugio*) and pinfish (*Lagodon rhomboides*) also avoided Aroclor 1254 at 10 mg/L, but pink shrimp (*Pinaeus duorarum*) and

sheepshead minnows failed to avoid this PCB in the range of 0.001 to 10 mg/L (Hansen *et al.* 1974).

2. Behavioral, physiological, and biochemical responses.–Miller and Ogilvie (1975) reported that concentrations in the range of 25 to 100 mg/L had no effect on temperature selection by brook trout. Significant increases in activity, however, as well as decreases in the brain neurotransmitters norepinephrine and dopamine, of the gulf killifish (*Fundulus grandis*) were noted following exposure to approximately 4 mg/L of Aroclor® 1242 (Fingerman and Russell 1980).

Koch *et al.* (1972) found that exposure of fathead minnows to Aroclor® 1254 and 1242 at 0.31 and 0.93 µg/L, respectively, for 4 mon had both inhibitory and stimulatory effects on Na^+-K^+ and Mg^{2+} ATPases in the brain, kidney, and liver. Davis *et al.* (1972), although reporting significant decreases in rainbow trout gill Mg^+ATPase caused by 4 mg/L of Aroclor® 1242, generally found poor correlation between ATPase inhibition and toxicity *in vivo*. Camp *et al.* (1974) reported that channel catfish (*Ictalurus punctatus*) following a 4-hr exposure to 8 mg/L of Aroclor® 1254 had a significant increase in serum GOT activity, suggesting hepatocellular damage.

3. Acute and chronic toxicity responses.–Most acute and chronic effects, however, for both fresh- and saltwater organisms were well below those levels reported to cause behavioral and biochemical effects. Pink shrimp showed chronic toxicity effects at 10 µg/L, and pinfish, although avoiding 10 mg/L, were found to be highly susceptible to disease during 14 to 45 days of exposure to 5 µg/L of Aroclor® 1254 (Hansen *et al.* 1971). In addition, another marine species, spot (*Leistomus xanthurus*), was found to rapidly store this chemical at water concentrations of 1 µg/L with maximum levels attained in 14 to 28 days (Hansen *et al.* 1971). Mauck *et al.* (1978) summarized the chronic effects of Aroclor® 1254 on brook trout, showing that the lowest concentration tested (0.43 µg/L) caused changes in backbone chemical composition (phosphorus and hydroxyproline concentrations); decreased growth was observed after 48 days exposure to 1.5 µg/L, and 3.1 µg/L caused direct toxicity after 118 days exposure. Thus, the no-effect concentration for brook trout growth and mortality was between 0.7 and 1.5 µg/L (Mauck *et al.* 1978). Coho salmon exposed to 4.4 µg/L Aroclor® 1254 until 4 wk post hatching experienced decreases in growth, egg hatchability, mean time to hatching, and alevin survival (Halter and Johnson 1974). The no-effect level for the fathead minnow in chronic tests was less than 1.8 µg/L (Nebeker *et al.* 1974), and the 30-day LC_{50}'s for this species for Aroclor® 1248 and 1260 were 4.7 and 3.3 µg/L, respectively (Defoe *et al.* 1978). Defoe *et al.* (1978) concluded that, because of the large bioconcentration factors associated with these chemicals, water concentrations below 0.1 µg/L, although not measurably affecting the fathead minnow, would be hazardous to consumers of the fish due to PCB tissue residues. MATC values for the sheepshead minnow were between 0.10 to 0.32 µg/L (Schimmel *et al.* 1974) and 10 to 32 µg/L (Hansen *et al.* 1975) for Aroclor® 1254 and Aroclor® 1016, respectively.

c) 2,4-D

1. Preference-avoidance responses.—The herbicide 2,4-D (2,4-dichlorophenoxyacetic acid) is synthesized from the chemical intermediate 2,4-dichlorophenol (2,4-DCP) and is commonly found either as the butoxyethanol ester or the dimethylamine salt of 2,4-D. This herbicide is used in forestry and agricultural applications to control unwanted vegetation and aquatic weeds. Various expected water concentrations of 2,4-D have been reported when estimated from different rates of application. Folmar (1978) estimated a water concentration of 0.1 mg/L at an application rate of 1.7 to 2.7 kg/ha, whereas Dodson and Mayfield (1979 a), using recommended application rates of 1.25 to 2.5 kg/100 m^2, estimated that water concentrations would be from 5 to 10 mg/L in a depth of 2.4 m and 10 to 20 mg/L in a depth of 1.2 m, representing active ingredient concentrations of 1.5 to 6.0 mg/L.

The lowest 2,4-D concentrations found to elicit avoidance behavior were 1.0 mg/L for the mosquitofish (Hansen *et al.* 1973 a) and the rainbow trout (Folmar 1976) as reported for the butoxyethyl ester and dimethylamine salt, respectively, and 0.1 mg/L for the sheepshead minnow exposed to butoxyethyl ester (Hansen 1969). Dodson and Mayfield (1979 a) found that ground Aqua-Kleen® (the commercial preparation of 2,4-D) caused a decrease in positive rheotaxis of rainbow trout after a 24-hr exposure to 2 mg/L and an increase in negative rheotaxis (downstream movement) after exposure to 4 mg/L for 24 hr. The decrease in positive rheotaxis would, in a natural stream community, result in increased downstream movement and is, in effect, a passive avoidance mechanism (Dodson and Mayfield 1979 a). Mayfly nymphs (*Ephemerella walkeri*) did not avoid 2,4-D at concentrations of 1.0, 10, or 100 mg/L (Folmar 1978).

Passive avoidance would be defined as the controlled or uncontrolled drift of an organism out of the area of chemical influence. Although this response would be protective in that the organism may not be in danger of direct toxic action from the chemical, its chances of survival may be diminished because of increased predation during this drift. Chemicals having a narcotic effect on fishes would be those most likely to elicit a passive avoidance response. Furthermore, there may be no direct relationship between passive and active avoidance. For example, rainbow trout did not actively avoid diquat (6,7-dihydrodipyrido[1,2:2',1'-C]-pyrazinedium dibromide) at concentrations of 0.1, 1.0, and 10 mg/L (Folmar 1976) but this species showed significant changes in rheotropic behavior which would lead to passive avoidance following a 24-hr diquat exposure to 0.5, 1.5, and 5.0 mg/L; these concentrations approach possible field exposure levels (Dodson and Mayfield 1979 b).

2. Behavioral, physiological, and biochemical responses.—Few studies were found relating sublethal behavioral, physiological, or biochemical effects in fishes to 2,4-D exposure. One exception was Cope *et al.* (1970) who reported delayed spawning of bluegill exposed to 5 and 10 mg/L 2,4-D; pathologic lesions were noted in the liver, vascular system, and brains of fish at all concentrations (0.1,

0.5, 1.0, 5.0, and 10.0 mg/L 2,4-D) for the first 28 days of exposure in experimental ponds.

3. Acute and chronic toxicity responses.—Mount and Stephan (1967) concluded that 0.3 mg/L 2,4-D of the butoxyethanol ester and 0.8 mg/L 2,4-D of the acid would not reduce the production rate of fathead minnows as measured by the laboratory fish production index (LFPI); for fathead minnows, the MATC for the ester was between 0.3 and 1.5 mg/L. The various formulations of 2,4-D showed considerable variation in their acute toxicities to salmonids and invertebrates. The butyl ester was found to be much more toxic than either the isooctyl ester or pure 2,4-D acid in 96-hr tests; the no-effect levels for rainbow trout were < 1.0, 10, and 50 mg/L, respectively (Meehan *et al.* 1974). Also, the 2,4-D herbicides had the broadest range of acute toxicities to scud (*Gammarus fasciatus*), extending from a 48-hr LC_{50} of 2.6 mg/L for the propylene glycol butoxyethyl ester of 2,4-D to no-effect at 100 mg/L for the dimethylamine salt (Sanders 1970); for *Daphnia magna* the 96-hr LC_{50} for 2,4-D butoxyethyl ester was estimated to be 5.9 mg/L. The most sensitive organism to the butoxyethyl ester tested by Sanders (1970) was the bluegill with a 48-hr LC_{50} of 1.1 mg/L; however, *Daphnia* were most sensitive to the dimethylamine salt (48-hr $LC_{50} = 4.0$ mg/L). Hansen (1969) reported a 24-hr LC_{50} of 7.0 mg/L for the sheepshead minnow.

The lowest avoidance thresholds reported were 1.0 mg/L for the mosquitofish and rainbow trout, and 0.1 mg/L for the sheepshead minnow, as noted earlier. The avoidance concentration for rainbow trout was slightly above the acute no-effect level reported for this species (Meehan *et al.* 1974). At this stage of research, however, it certainly appears that avoidance may occur at concentrations approximating those which have no acute or chronic toxic effects, and that both important behavioral changes, as well as chronic toxicity, could occur in the field if the expected water concentrations (0.1 to 20 mg/L) reported earlier are accurate.

V. Organophosphates

Organophosphates are a diverse array of compounds which are generally less toxic and not as persistent as the organochlorine pesticides they have replaced. This is also an unusual class of compounds from a toxicological viewpoint in that the mode-of-action of these chemicals was known at an early stage of their development. Primarily, these compounds (or their hydrolytic products) affect the nervous system at the neuronal synapse by inhibiting the enzyme, acetylcholinesterase (AChE), responsible for the breakdown of the chemical messenger, acetylcholine. However, it is possible that the mortality of fishes following acute exposure may be the result of physiological damage in addition to AChE inhibition, because parathion, for example, a powerful AChE inhibitor, is not among the most toxic of the organic phosphorus insecticides (Pickering *et al.* 1962). Knowledge of the mode-of-action subsequently influenced later research so that a considerable number of data exist on the biochemical effects of organo-

phosphates on aquatic organisms. Surprisingly, however, considering the importance of proper nerve function to behavioral responses, relatively few studies were found which examined the ability of fishes to avoid these pesticides.

a) Malathion

1. Preference-avoidance responses.–Mulla and Mian (1981) have recently reviewed the biological and environmental impacts of malathion on aquatic organisms. Hansen (1972) reported that malathion concentrations of 100 and 1,000 μg/L had no effect on salinity selection by the mosquitofish, but this species would avoid 50 and 500 μg/L if given a clean water refuge (Hansen *et al.* 1973 a). However, grass shrimp and sheepshead minnows would not avoid malathion at 10, 100, or 1,000 μg/L (Hansen 1969, Hansen *et al.* 1973 b).

2. Behavioral, physiological, and biochemical responses.–Perhaps the most sensitive behavioral response reported was decreased temperature selection by 2-yr-old common shiners (*Notropis cornutus*) caused by a 24-hr exposure to malathion at 0.25 μg/L (Domanik and Zar 1978). Atlantic salmon also lowered their selected temperature by 2°C following exposure to 25 μg/L of malathion (Peterson 1976). This change in selected temperature, noted for other compounds in this review, was suggested by Peterson (1976) to be of immediate, short-term survival value to the fish because, generally, those substances that increase the preferred temperature are more toxic at low temperatures and *vice versa.*

A 10 μg/L concentration of malathion caused a 30% reduction in the brain AChE of the spot after 26 wk of exposure; however, no changes in growth or mortality were noted (Holland and Lowe 1966). Post and Leasure (1974) reported that malathion at 90, 112, and 200 μg/L caused an approximately 50% reduction in the brain AChE residues and a 23 to 45% reduction in the physical activity index (as measured by swimming performance) of brook trout, rainbow trout, and coho salmon, respectively. A 20 to 25% reduction in AChE activity was observed in goldfish following a 6-hr exposure to 100 μg/L of malathion, and largemouth bass (*Micropterus salmoides*) exhibited reduced AChE activity to $<$ 24% of normal following acute exposure (2 hr 40 min) to 500 μg/L (Wiess 1959, 1961). Christensen and Reidel (1981) reported a threshold of 23 mg/L for inhibition of lipase *in vitro.*

3. Acute and chronic toxicity responses.–A malathion concentration of 200 μg/L did not reduce the fathead minnow production rate during chronic exposure, and the MATC was estimated between 200 and 580 μg/L (Mount and Stephan 1967). Ninety-six hr LC_{50}'s for bluegill were 120, 55, and 46 μg/L at acclimation temperatures of 12.7°, 18.3°, and 23.8°C, respectively (Macek *et al.* 1969). The sheepshead minnow had a 96-hr LC_{50} of 51 μg/L and the MATC was estimated to be greater than 4.0 μg/L but less than 9.0 μg/L. Bluegill was the most sensitive warmwater species tested by Pickering *et al.* (1962) with a 96-hr LC_{50} of 90 μg/L malathion.

The lowest malathion avoidance threshold reported (50 μg/L for mosquito-

fish) (Hansen *et al.* 1973 a) was below most concentrations reported to cause deleterious biochemical effects on freshwater fishes and also well below the MATC for fathead minnows. It appeared, however, that sheepshead minnows would not avoid either chronically or acutely toxic malathion concentrations, at least within 60 min of exposure (Hansen 1969).

b) Fenitrothion

1. Preference-avoidance responses.—Scherer (1975) reported the only direct avoidance response to fenitrothion with the threshold concentration for goldfish around 10 μg/L.

2. Behavioral, physiological, and biochemical responses.—The above avoidance threshold was the lowest concentration having a significant effect on any of the behavioral endpoints considered. For example, 100 μg/L fenitrothion was found to increase the cough response and reduce feeding of the coho salmon, while 230 to 480 μg/L were required before physiological impairment occurred (Bull and McInerney 1974). Fenitrothion concentrations of 100 and 1,000 μg/L, after a 15 to 16 hr exposure, caused a reduction in the ability of Atlantic salmon to defend territories 6 days following treatment (Symons 1973); a 24-hr exposure to 1,000 μg/L also reduced this species' ability to avoid predation by brook trout and completely inhibited their ability to learn to avoid an electric shock (Hatfield and Anderson 1972, Hatfield and Johansen 1972). Peterson (1974) reported that a 24-hr exposure of brook trout to 500 μg/L adversely affected swimming performance by causing a 17% decrease in the mean critical velocity and a 35% reduction in power output. The highest fenitrothion concentration which did not cause significant behavioral changes in the frog, *Rana clamitans*, was 1,000 μg/L, but 2,000 and 3,000 μg/L did cause a significant decrease in multidirectional swimming (Lyons *et al.* 1976).

Lockhart *et al.* (1973, as reported by Symons 1977) found a 30% reduction in brain AChE and a 50% reduction in serum AChE at a fenitrothion concentration of 4,600 μg/L after exposure from 1 to 6 days. Tucker and Leitzke (1979), however, concluded that cholinesterase inhibition by organophosphates was not found to occur at treatment levels very different from those which produced mortality in fishes.

3. Acute and chronic toxicity testing.—Zitko and Cunningham (1975) reported that no fenitrothion-induced mortality occurred with Atlantic salmon at nominal concentrations less than 630 μg/L in 96 hr, and Eidt (1975) found that, although some stoneflies and mayflies were killed in streams containing 6.4 μg/L fenitrothion, the benthos was not seriously depleted. No chronic toxicity data for fishes were available.

Given limited data, it appears that avoidance behavior is, potentially, a very sensitive indicator of sublethal stress by fenitrothion. However, because of the expected rapid degradation of fenitrothion under field conditions, avoidance, most likely, would not persist.

c) Parathion

1. Preference-avoidance responses.–Kynard (1974) reported the abilities of susceptible and resistant populations of mosquitofish to avoid insecticides. Of the four compounds tested, susceptible fish would most likely avoid parathion, and resistant fish were most likely to avoid parathion and toxaphene. The lowest parathion concentrations avoided by susceptible and resistant mosquitofish were 200 and 1,000 μg/L; 24-hr LC_{50}'s were 20 and 2,000 μg/L, respectively (Kynard 1974). These results indicated that resistant fish avoided acutely toxic concentrations to a greater extent than susceptible fish and, hence, the implication was that selection favored those individuals capable of avoiding potentially harmful insecticide concentrations (Kynard 1974).

2. Behavioral, physiological, and biochemical responses.–Concentrations of 0.1 μg/L ethyl and methyl parathion caused increased activity by grass shrimp after exposure for 72 hr, which, in turn, rendered them more susceptible to predation by gulf killifish (Farr 1977). In a related study, Farr (1978) exposed grass shrimp and juvenile sheepshead minnows to 0.024, 0.119, and 0.475 μg/L methyl parathion for 24 hr prior to the introduction of a single gulf killifish. At all concentrations, predation on grass shrimp increased after a 5-day exposure, indicating that low concentrations of this insecticide can alter the relative proportions of prey in a predator diet (Farr 1978).

Goldfish, following a 24-hr exposure to 330 μg/L, changed their behavioral responses to the perception of odor and flow rates (Rand *et al.* 1975), and also reduced their activity (Rand 1977); this concentration was approximately half of the 48-hr LC_{50} (Rand *et al.* 1975). The AChE activity in this species was reduced to < 40% of normal after a 24-hr exposure to 100 μg/L parathion (Weiss 1959), while concentrations of 500 μg/L reduced AChE activity to 24.3 and 81.5% of normal after 24-hr exposures of largemouth bass and fathead minnows, respectively (Weiss 1961).

3. Acute and chronic toxicity responses.–Mulla and Mian (1981) recently reviewed the biological effects of parathion, and did not report any chronic toxicity tests *per se* for parathion. Acute toxicity ranged from a 72-hr LC_{50} of 20 μg/L for the green sunfish to a 96-hr LC_{50} of 1,400 μg/L for the fathead minnow and bluegill sunfish (Davey *et al.* 1976, Henderson and Pickering 1958). Jarvinen and Tanner (1982) reported a 96-hr LC_{50} for methyl parathion of 5.36 mg/L for the fathead minnow, while in chronic studies growth effects were observed in the range of 0.31 to 0.38 mg/L. Jarvinen and Tanner estimated a half-life of 18 days for methyl parathion but Faust and Gomaa (1972, as reported by Livingston 1977) reported that parathion was more persistent under certain environmental conditions in aquatic systems than previously expected with a half-life of 108 days (144 days for its more toxic metabolite paraoxon). Thus, additional research concerning the chronic effects of parathion are warranted. Avoidance behavior did not appear to be a particularly sensitive indicator of parathion poisoning but available data are extremely limited.

VI. Miscellaneous compounds

a) Phenol

1. Preference-avoidance responses.—Phenol has been perhaps the most consistently studied compound which, generally, does not elicit an active avoidance response even at acutely lethal concentrations. Sprague and Drury (1969) found that rainbow trout would not avoid phenol at concentrations ranging from 0.001 to 10 mg/L, and Summerfelt and Lewis (1967) reported that green sunfish would not avoid 20 mg/L. The minnow (*Phoxinus phoxinus*) would not avoid 4 mg/L of phenol and generally became intoxicated at higher concentrations (Jones 1951).

2. Behavioral, physiological, and biochemical responses.—Although Stott and Buckley (1979) found that *Phoxinus* would not avoid 4, 8, and 10 mg/L of phenol, they did note depressed activity and altered shoaling behavior at all concentrations, and uncontrolled and erratic swimming at approximately 7 mg/L. A phenol concentration of 7 mg/L was also the lowest concentration causing increased predation on rainbow trout after a 96-hr exposure (Schneider *et al.* 1980), and 7.5 mg/L was the lowest concentration tested which caused a significant decrease in the selected temperature of brook trout (Miller and Ogilvie 1975). Hiatt *et al.* (1953), however, reported that phenol at concentrations as low as 2 mg/L would disperse a school of *Kuhlia sandvicenses.* These behavioral thresholds generally appeared high considering that fishes could apparently detect phenol at much lower concentrations, as determined by conditioning studies. Based on a conditioned flight reflex, Marcstrom (1959) determined that the reaction threshold of roach to phenol was approximately 0.9 mg/L; Hasler and Wisby (1950) concluded that the lower limit of phenol detection for the bluntnose minnow (*Pimephales notatus*) was 0.0005 mg/L. No data were available which related specific biochemical effects with phenol concentrations.

3. Acute and chronic toxicity responses.—The only chronic value reported was 2.56 mg/L of phenol for the fathead minnow (Holcombe *et al.* as reported by USEPA 1980 f). Mean acute values for the goldfish, fathead minnow, bluegill sunfish, and rainbow trout were 44.5, 36.0, 16.4, and 10.2 mg/L, respectively (USEPA 1980 f).

Although avoidance behavior does not appear to be a sensitive indicator of phenol poisoning, several other deleterious behavioral effects were noted at subacute concentrations.

b) Pulp and paper mill effluents

1. Preference-avoidance responses.—Generalizations concerning the biological effects of pulp and paper mill effluents were difficult to make because of the variable composition of mill wastes. Toxicity of these effluents depends largely on the species of tree utilized and the chemical treatment of the wood pulp. Effective concentrations were generally reported as a % on a volume/volume

basis, or as a fraction of the 96-hr LC_{50} (toxic unit). Walden (1976) has presented a comprehensive review of the toxicity of pulp and paper mill effluents to aquatic organisms, and he noted that the impact of these discharges on receiving waters "results from the integrated action of oxygen demand, suspended solids, pH, color, and toxicity."

Considerable research has been conducted on the avoidance responses of fish to mill effluents. Threshold concentrations were generally reported in the range of 1 to 5%, but in some cases fishes avoided at mill effluent levels of 0.1%. Kraft mill effluent (KME) concentrations within this range were found to have variable effects on chinook salmon (*Oncorhynchus tshawytscha*) production caused by differences in the source and extent of treatment of the effluent, and possibly by differences in season (Seim *et al.* 1977). Jones *et al.* (1956) tested the avoidance responses of steelhead trout and chinook and coho salmon to several different mill wastes in two types of chambers. In a modified gradient tank chinook salmon were most sensitive, avoiding 1.5 to 4.3% whole sulfate waste; coho salmon avoided 4.3 to 4.8%, but steelhead trout showed no avoidance over this range of concentrations. In a channeled avoidance tank, chinook salmon showed only slight avoidance to 2.5% whole sulfate waste prepared with combined condensates and black liquor; slight preference to 1.25% was also noted. Atlantic salmon were found to have a broad avoidance threshold because fish appeared to equally avoid concentrations in the range of 0.001% to 10% bleached kraft mill effluent (BKME) (Sprague and Drury 1969). These authors concluded that 0.1% BKME would likely cause avoidance by salmonids under natural conditions if given a choice of clean water with suitable habitat, otherwise salmon would not avoid almost lethal levels (15% BKME was the lethal threshold for Atlantic salmon as reported by Sprague and Drury 1969). Columbia river smelt (*Thaleichthys pacificus*) avoided channels containing sulfate and mixed sulfate and sulfite paper mill wastes by selecting channels with unaltered river water (Smith and Saalfield 1955 as reported by Jones *et al.* 1956). Kelso (1977) found that yellow perch (*Perca flavescens*) apparently avoided a pulp and paper mill discharge area, whereas white suckers and longnose suckers (*Catostomus catostomus*) were abundant in the effluent. Benthic invertebrates were also extremely abundant, which suggested that for certain species the feeding response counteracted the avoidance reaction to the effluent.

Marine species were also sensitive to BKME; pinfish and the gulf killifish showed significant avoidance to 0.1% with an estimated threshold level (that concentration having no effect) of 0.06% (Livingston *et al.* 1976, Lewis and Livingston 1977). Results of an estuarine field survey indicated that considerably fewer pinfish were taken in BKME-influenced areas than in control areas; after water quality improvement, however, no change was observed in the field distribution of pinfish for over one yr, indicating that fish distribution could be determined by environmental factors other than water quality *per se* (Livingston *et al.* 1976).

Wildish *et al.* (1977) examined the avoidance response of herring (*Clupea harengus*) to whole pulp mill effluent (PME) and several of its major constituents. Herring were sensitive to sodium lignosulfonate and humic acid, with avoidance thresholds at nominal concentrations of 0.1 to 0.3 mg/L and 0.1 to 0.2 mg/L, respectively. These authors suggested that "herring avoided long-chain complex molecules such as lignosulfonates and perhaps lignin in PME rather than resin acids and breakdown products of low molecular weight which are known to be relatively toxic."

2. **Behavioral, physiological, and biochemical responses.**—Alterations in respiration and in blood characteristics were also sensitive indicators of KME poisoning. A direct relationship was observed between respiration rate and neutralized KME concentration over the range of 5 to 40% for coho salmon (Schaumberg *et al.* 1967). Walden *et al.* (1970) also reported minimum cough response thresholds (no detectable responses) for rainbow trout at 1.1 and 4.0% for neutralized KME and BKME, respectively. These authors concluded from cough response observations that trout acclimated to sublethal concentrations of kraft effluents, and the time required for acclimation was concentration-dependent. This conclusion was contrary to that of McLeay and Brown (1979), who reported that coho salmon remained in a state of chronic stress and failed to acclimate following prolonged exposure to pulp mill effluents. This statement was based on observed changes in intermediary metabolism for BKME-exposed fish for 30, 90, and 200 days. Coho salmon exposed to untreated BKME at concentrations of 0.05 of the 96-hr LC_{50} had decreased liver and muscle glycogen reserves and decreased serum albumin levels following a 30-day exposure; plasma lactic acid was elevated at all test concentrations after 200 days of exposure (McLeay and Brown 1979). Based on elevated plasma glucose levels, threshold effect values ranged from 0.04 to 0.16 of the 96-hr LC_{50} for coho salmon (McLeay 1977).

3. **Acute and chronic toxicity responses.**—Whittle and Flood (1977) reported that the BKME 96-hr LC_{50} ranged from 14 to 49% for rainbow trout depending on test conditions. They also found a significant reduction in the rate of weight increase following an 18-day exposure to 6% BMKE and a definite taint in flavor was observed in 50% or more of the rainbow trout exposed to 3% BKME for 144 hr. Walden (1976), summarizing the sublethal effects of kraft mill effluents on aquatic organisms, found that the threshold concentrations for various sublethal parameters, including respiration and biochemical effects, generally fell between 0.05 and 0.1 of the 96-hr LC_{50}. Most avoidance thresholds were within this range or below, and many were also below the 3% concentration reported to cause flesh tainting in rainbow trout (Whittle and Flood 1977). Furthermore, avoidance to pulp and paper effluents has been shown to alter fish distributions and movements under natural conditions. Avoidance behavior, therefore, should be an important consideration when setting discharge limitations for this type of effluent.

Table VII. *Lowest total residual chlorine concentrations (arranged in increasing order from most sensitive species to least sensitive species) causing avoidance in freshwater and saltwater tests as reported for a variety of fish species and testing procedures.*

Species	Avoidance Concentration (mg/L)	Reference
	Freshwater	
Salmo gairdneri (rainbow trout)	0.01	Sprague & Drury (1969)
Oncorhynchus kisutch (coho salmon)	0.05-0.10	Cherry *et al.* (1979)
Micropterus punctulatus (spotted bass)	0.05-0.20	Cherry *et al.* (1977 b)
Notropis rubellus (rosyface shiner)	0.05-0.20	Cherry *et al.* (1977 b)
Catostomus commersoni (white sucker)	0.10-0.20	Cherry *et al.* (1979)
Cyprinus carpio (carp)	0.10-0.21	Cherry *et al.* (1979)
N. cornutus (common shiner)	0.11-0.21	Cherry *et al.* (1978)
N. galacturus (whitetail shiner)	0.11-0.22	Giattina *et al.* (1981)
N. spilopterus (spotfin shiner)	0.21	Giattina *et al.* (1981)
Ictalurus punctatus (channel catfish)	0.20-0.41	Cherry *et al.* (1979)
	Marine	
O. kisutch (coho salmon)	0.002	Stober *et al.* (1980)
Morone americana (white perch)	0.02	Meldrim *et al.* (1974)
Lagoden rhomboides (pinfish)	0.02-0.04	Cripe (1979)
Menidia menidia (Atlantic silverside)	0.06	Meldrim & Fava (1977)
Chromis punctipinnis (blacksmith)	0.08-0.10	Hose & Stoffel (1980)
Cymatogaster aggregata (shiner perch)	0.175	Stober *et al.* (1980)
Morone saxatilis (striped bass)	0.29	Middaugh *et al.* (1977)

c) Chlorine and chlorinated effluents

1. Preference-avoidance responses.—Chlorine has been perhaps the most thoroughly studied chemical with regard to the preference-avoidance reactions of fishes. This is primarily because chlorine is a major toxic component of sewage effluents from waste treatment facilities and cooling system discharges from power generating facilities; both are important sources of water pollution in the United States.

A basic understanding of chlorine chemistry in water is necessary to understand the behavioral responses of fishes to the element. For a detailed discussion of chlorine chemistry in aqueous solutions, the reader should consult Sawyer and McCarty (1967). For this discussion, suffice it to say that chlorine, when dissolved in freshwater, is composed of two major constituents: the free residual (FRC) and the combined residual (CRC), the sum of which is the total residual chlorine (TRC). The FRC is composed of hypochlorous acid (HOCl) and hypochlorite ions (OCl^-); however, HOCl is generally the constituent of concern because of its greater toxicity (Mattice *et al.* 1981). The CRC, in most freshwaters, is predominantly monochloramine (NH_2Cl). It has been firmly established that the relative ratios of these components (FRC versus CRC) strongly influence the toxic action of chlorine (Heath 1977), and the avoidance responses of fishes to chlorine (Cherry *et al.* 1977 a, Fava and Tsai 1976). An in-depth discussion of the avoidance responses in relation to the various TRC constituents would not be appropriate to this discussion. In general, it appears that fish more readily avoid TRC when HOCl is present than when monochloramine predominates (Cherry *et al.* 1977 a, 1979). The avoidance response of fishes to chlorine is species-specific and much of the data presented in the literature are summarized in Table VII.

Environmental factors influencing the avoidance response were generally reported for saltwater organisms. For example, chlorine avoidance by white perch (*Morone americana*) and Atlantic silverside (*Menidia menidia*) was shown to be significantly affected by acclimation temperature, salinity, size of specimens, and light intensities; also interactions between variables, such as temperature-pH and salinity-pH, had significant effects on avoidance concentrations (Meldrim *et al.* 1974, Meldrim and Fava 1977). Hose and Stoffel (1980) found a direct correlation between fish weight (the blacksmith, *Chromis punctipinnis*) and total residual oxidant (TRO) avoidance concentrations. In addition, these authors reported significant changes in avoidance behavior caused by the presence of food organisms and the degree of starvation of the test organism. Blacksmith tolerated higher TRO concentrations when food was present on the chlorinated side of the tank; starved fish also spent more time foraging on the chlorinated side, not avoiding until concentrations reached 0.33 mg/L, as opposed to an avoidance concentration of 0.18 mg/L for saturated fish (Hose and Stoffel 1980).

Temperature preference was shown to be a significant factor influencing avoidance behavior for some species. This could be a particularly important factor considering that chlorinated effluents from many industrial processes are

associated with water heated above ambient conditions. Spotfin shiners (*Notropis spilopterus*), for example, after being attracted into water heated to their preferred temperature, avoided CRC concentrations approximately double those previously avoided when temperature selection was not a factor (0.38 vs. 0.20 mg/L, respectively (Giattina *et al.* 1981)). Similar results have been reported for other freshwater species by Cherry *et al.* (1982). Shiner perch (*Cymatogaster aggregata*) demonstrated a significant preference for TRO concentrations in the range of 0.01 to 0.10 mg/L in heated seawater, not avoiding until concentrations were approximately 0.18 mg/L (Stober *et al.* 1980). As noted by Stober *et al.*, the 96-hr LC_{50} for shiner perch in chlorinated seawater was 0.071 mg/L TRO (Thatcher 1978), so that continuous thermal discharges with 0.071 to 0.100 mg/L TRO would attract and possibly prove fatal to shiner perch.

Time of exposure generally was not considered in most avoidance studies; however, Fava and Tsai (1976 and 1978) demonstrated that this was an important consideration. Blacknose dace (*Rhinichthys atratulus*) showed an immediate avoidance response to 0.51 mg/L TRC (92% CRC). However, when given a longer time of exposure, this species avoided TRC as low as 0.07 mg/L (86% CRC) with a median avoidance time of 145.7 min (Fava and Tsai 1978). This illustrated the fact that fish can generally exploit given concentrations of chlorine for limited periods of time, without incurring significant detrimental effects before moving out of the impacted area, a conclusion supported in field observations by Osborne *et al.* (1981).

Considerable documentation was found on chlorine avoidance responses under field conditions. After surveying 149 sewage treatment plants, Tsai (1973) reported that fish species diversity indices, the number of fish, and the number of species were lowest at stations immediately below chlorinated outfalls but gradually increased at stations farther downstream. Fava and Tsai (1976) concluded that chloramines were the principal factors in domestic sewage effluents which caused fish avoidance behavior. Recently, Osborne *et al.* (1981) did not find any significant differences in the numbers of fish collected in a chlorinated sewage treatment effluent vs. control areas. In-stream bioassays, however, showed the effluent to be toxic. From this information, the authors concluded that fish moved into the chlorinated plume but moved out before they were adversely affected. The effluent was concentrated along one bank with relatively fresh water along the other side so fish could make "periodic excursions for feeding or other activities" (Osborne *et al.* 1981).

Giattina *et al.* (1981) reported the avoidance of a heated, intermittently chlorinated discharge by warmwater fishes. At TRC concentrations greater than 0.15 mg/L significant reductions in fish abundance were observed. Ninety-five % confidence limits for the avoidance threshold concentrations for summer and fall conditions were 0.19 to 0.28 and 0.23 to 0.42 mg/L TRC, respectively. Close similarity between laboratory and field avoidance concentrations were noted, indicating the predictive value of site-specific laboratory studies (Giattina *et al.*

1981; see also Cherry *et al.* 1977 b). Grieve *et al.* (1978), using radiotelemetry tracking, found that white bass (*Morone chrysops*) avoided preferred habitat areas below a chlorinated effluent when TRC concentrations were in the range of 0.035 to 0.05 mg/L. Preliminary underwater observations of a power plant discharge into an estuarine area, showed that resident fish species temporarily left the effluent area when TRO concentrations exceeded 0.10 mg/L (Hose and Stoffel 1980). Based on laboratory avoidance responses, Stober *et al.* (1980) concluded that ". . . lethal or chronic effects observed in laboratory bioassays should not occur in the field as long as discharges are sited which do not disturb established or preferred migration routes through coastal and estuarine areas."

2. Behavioral, physiological, and biochemical responses.—Other behavioral and physiological alterations were noted over the same range of concentrations which caused avoidance. Dandy (1972), for example, reported a marked increase in activity of brook trout exposed to a concentration of 0.08 mg/L TRC, and the coughing rate of rainbow trout exposed intermittently to 0.40 mg/L TRC (mostly FRC) increased 15 times over pre-exposure levels during the first four chlorine pulses (Bass and Heath 1977). This concentration also caused a 56% decrease in heart rate after five pulses, but change in the coughing rate was the most sensitive indicator of chlorine poisoning, with peak responses noted about 20 min before maximal cardiac and ventilatory responses occurred (Bass and Heath 1977). Similar increases in cough rates were reported for chloramine exposures by Travis and Heath (1981).

Hyperplasia and swelling of gill epithelial cells were found in bluegills following intermittent exposure to 0.20 or 0.30 mg/L TRC, predominantly FRC (Bass *et al.* 1977). Buckley *et al.* (1976), conducting saltwater tests, reported an increase in immature erythrocytes in coho salmon following a one-wk exposure to 3.6% chlorinated municipal sewage effluent with a TRC content of 0.03 mg/L; an effluent concentration of 1.1% (0.009 mg/L TRC) also caused significant reductions in hemoglobin levels after a 2-wk exposure.

3. Acute and chronic toxicity responses.—Reviews of the toxicity of chlorine to aquatic organisms have been presented by Brungs (1973 and 1976) and Mattice and Zittel (1976). Few chronic data for fish were available; most studies have concentrated on acutely toxic effects. Arthur and Eaton (1971) reported that 0.0165 mg/L chloramine had no effect on the fathead minnow following 21 wk of exposure. In saltwater tests, Middaugh *et al.* (1977) found reduced hatchability by developing embryos of striped bass exposed to TRC concentrations of 0.01 and 0.07 mg/L (1 to 3% salinity) but avoidance behavior was not noted until concentrations were 0.29 to 0.32 mg/L (see Table VII). The MATC for coho salmon in saltwater was 0.003 to 0.009 mg/L TRC (Buckley *et al.* 1976). Mattice and Zittel (1976) estimated the threshold chlorine concentrations for chronic effects in fresh- and saltwater to be 0.0015 and 0.02 mg/L, respectively. These thresholds were derived from a graphical summary of the toxic effects of chlorine on plants, invertebrates, and vertebrates, most of which were reported as 50%

effect levels. Degraeve *et al.* (1979) recommended a TRC criterion of 0.003 to 0.005 mg/L for protecting freshwater aquatic life, and stated that 0.02 mg/L would be the most suitable level for protecting saltwater organisms. In general, these criteria were below concentrations which caused avoidance (see Table VII) or other biochemical and physiological effects reported in the literature.

Summary

Broad statements regarding the avoidance of aquatic contaminants by fishes are difficult to make because of the variety of species and experimental designs used to test behavioral responses. Variations in the modes- and sites-of-action of chemicals, biological and chemical transformation from parent compounds to more or less toxic forms, direct or secondary alterations of water quality or physical habitat characteristics by chemicals, temporal changes in biological susceptibility, and intra- as well as interspecific variability in behavior, are all factors which tend to preclude easy generalization.

Our review found the preference-avoidance response to be a sensitive indicator of sublethal poisoning in fishes for many of the chemicals examined, particularly when compared with other behavioral endpoints, with biochemical or physiological alterations, and with acute toxicological effects. Preference-avoidance concentrations for several of the chemicals discussed in the review are summarized in Table VIII with 96-hr LC_{50} data and chronic values for a few species. With the exception of cadmium, PCBs, malathion, and under some conditions, parathion, most other chemicals elicited avoidance responses (preferences responses in the case of mercury) at concentrations generally much less than LC_{50} levels. Chronic values for comparison are scarcer but, again, for some chemicals avoidance thresholds were below supposed safe levels. Some fish species responded sensitively to copper, zinc, nickel, and chlorine, whereas lead, PCBs, and malathion were not readily detected by those species listed in Table VIII. As noted earlier, pulp mill wastes were also effective at eliciting avoidance at subchronic concentrations. It is immediately apparent that no statistical correlation exists between those concentrations eliciting avoidance and those concentrations causing acute or chronic toxicity; this supports the conclusions of Sprague and Drury (1969) and Sutterlin (1974). For this reason the predictive capability of an avoidance test for estimating chronic toxicity appears to be severely limited.

Natural communities, for the most part, are rarely exposed to acutely toxic levels of most pollutants. More often, an organism has to compensate for the deleterious effects of prolonged exposure to low levels of a pollutant. Failure to compensate would result in either a gradual decline in the quality of the fish stock (*e.g.*, tainting, reduced growth rate) or elimination of sensitive species altogether (by direct mortality or reproductive failure) from the area of impact. Aquatic organisms are capable of responding to chemical stress with a variety of compensatory mechanisms: behavioral, biochemical, and physiological. In gener-

Table VIII. *Comparison of avoidance concentrations with acute and chronic toxicity data for several fish species as referenced in text.*

Species	Chemical	Avoidance concentration (μg/L)	96-hr LC_{50} (μg/L)	Chronic values (μg/L)
		Freshwater		
Gambusia affinis[a] (mosquitofish)	parathion	200	20[b]	[c]
G. affinis[d] (mosquitofish)	parathion	1,000	2,000[b]	[c]
Salmo gairdneri (rainbow trout)	cadmium	50	1	[c]
	copper	6.4,0.1,70	17	19
	lead	26	1,170	5.6,24
	mercury	0.2[e]	220	[c]
	nickel	23.9	35,500	350
	zinc	5.6,50	93	277
	2,4-D	1,000[f]	1,000[g]	[c]
		Saltwater		
Cyprinodon variegatus (sheepshead minnow)	2,4-D	100	7,000[b]	[c]
	malathion	>1,000	51	4-9[h]
	Aroclor® 1254	>10,000	[c]	0.10-0.32[h]
Oncorhynchus kisutch (coho salmon)	chlorine	2	80[i]	3-9[h]

[a] Susceptible fish (Kynard 1974).
[b] 24-hr TLm.
[c] Data not available.
[d] Resistant fish (Kynard 1974).
[e] Significant attraction (Black and Birge 1980).
[f] Dimethylamine salt of 2,4-D (Folmar 1976).
[g] Butyl ester of 2,4-D (Meehan *et al.* 1974).
[h] Maximum acceptable toxicant concentration range.
[i] Test duration < 120 hr (Holland 1960, as reported by Mattice and Zittel 1976).

al, we found that behavioral responses precede biochemical alterations, a conclusion which is supported by Hochachka and Somero (1973) who state that "biochemical adaptations often appear to be 'last resort' responses, made if and only if the organism lacks behavioral or physiological avenues of escape from an environmental stress."

The ability of an organism to avoid acutely harmful concentrations of a toxic substance is of obvious short-term value to that organism. However, if avoidance is an adaptive behavior which confers some long-term survival advantage to a species exposed to a chemical stress, then a significant number of that species must either avoid concentrations known to cause chronic effects or avoid concentrations within sublethal *times* of exposure. In general, avoidance studies have stressed the concentrations at which avoidance first occurred and disregarded the time required for avoidance. Due to the nature of most experimental designs, however, avoidance responses were generally measured within 60 min. As noted earlier, Fava and Tsai (1978) found that extending the exposure time could significantly decrease the avoidance threshold. Thus, when considering reaction time for avoidance (that time required for avoidance to occur), particularly when it occurs at chronic concentrations, there are vast differences between avoidance thresholds and chronic values for some chemicals. It is apparent, based on reaction time, that fishes may be capable of exploiting, for limited periods of time, areas of the aquatic environment at concentrations above acute or chronic toxicity thresholds. Field observations (*e.g.*, Kelso 1977, Osborne *et al.* 1981) tend to support this conclusion.

Avoidance by fishes of unfavorable and, in some instances, harmful changes in water quality have been observed for a broad range of species and chemical contaminants under laboratory conditions. Although extensive field work is needed to further validate laboratory results, data currently available from natural ecosystems tend to support the underlying assumption that avoidance is an ecologically significant behavior by which an organism can adapt to, or compensate for, potentially lethal changes in water or habitat quality.

Fishes may avoid aquatic contaminants or succumb to their lethal effects; the result may be the loss of a fishery resource from a given area for an indefinite period of time. According to Cairns (1981), "the most important of the future needs in biological assessment of pollution are: (a) development of a predictive capability; and (b) means of validating the accuracy of the predictions which will in turn enable corrections to be made when the predictions are in error." If aquatic toxicologists and ecologists are to predict or estimate the impact of a given substance on an aquatic system, it is evident that avoidance behavior of the fish species concerned should be considered. Site-specific testing of this nature requires the development of a standardized approach to avoidance testing which will make results comparable and provide a broader data base for estimating the environmental impact of a substance.

References

Anderson, J. M.: Effect of sublethal DDT on the lateral line of brook trout, *Salvelinus fontinalis*. J. Fish. Res. Board Can. **25**, 2677 (1968).

_____ Assessment of the effects of pollutants on physiology and behavior. Proc. Roy. Soc. Lond. **177**, 307 (1971).

_____, and M. R. Peterson: DDT: Sublethal effects on brook trout nervous system. Science **164**, 440 (1969).

_____, and H. B. Prins: Effects of sublethal DDT on a simple reflex in brook trout. J. Fish. Res. Board Can. **27**, 331 (1970).

Andrew, R. W., P. V. Hodson, and D. E. Konasewich (eds.): Proceedings of a workshop on toxicity to biota of metal forms in natural waters. International Joint Commission, Windsor, Ontario, Canada (1976).

Andros, J. D., and R. R. Garton: Acute lethality of copper, cadmium, and zinc to northern squawfish. Trans. Amer. Fish. Soc. **109**, 235 (1980).

Arthur, J. W., and J. G. Eaton: Chloramine toxicity to the amphipod *Gammarus pseudolimneus* and the fathead minnow (*Pimephales promelas*). J. Fish. Res. Board Can. **28**, 1841 (1971).

Bass, M. L., and A. G. Heath: Cardiovascular and respiratory changes in rainbow trout, *Salmo gairdneri*, exposed intermittently to chlorine. Water. Res. **11**, 497 (1977).

_____, C. R. Berry, Jr., and A. G. Heath: Histopathological effects of intermittent chlorine exposure on bluegill (*Lepomis macrochirus*) and rainbow trout (*Salmo gairdneri*). Water Res. **11**, 731 (1977).

Becker, C. D., and M. G. Wolford: Thermal resistance of juvenile salmonids sublethally exposed to nickel, determined by the critical thermal maximum method. Environ. Pollut. **21**, 181 (1980).

Bengtsson, B. E., C. H. Carlin, A. Larson, and O. Svanberg: Vertebral damage to minnows *Phoxinus phoxinus* L. exposed to cadmium. Ambio **4**, 166 (1975).

Benoit, D. A., and G. W. Holcombe: Toxic effects of zinc on fathead minnows *Pimephales promelas* in soft water. J. Fish. Biol. **13**, 701 (1978).

_____, E. N. Leonard, G. M. Christensen, and J. T. Fiandt: Toxic effects of cadmium on three generations of brook trout (*Salvelinus fontinalis*). Trans. Amer. Fish. Soc. **105**, 550 (1976).

Biesinger, K. E., and G. M. Christensen: Effects of various metals on survival, growth, reproduction, and metabolism of *Daphnia magna*. J. Fish. Res. Board Can. **29**, 1691 (1972).

Black, J. A., and W. J. Birge: An avoidance response bioassay for aquatic pollutants. Research Rept. No. 123, Univ. of Kentucky, Water Resources Res. Inst., Lexington, KY (1980).

Brungs, W. A.: Effects of residual chlorine on aquatic life. J. Water Poll. Contr. Fed. **45**, 2180 (1973).

_____ Effects of wastewater and cooling water chlorination on aquatic life. U.S. Environmental Protection Agency, EPA-600/3-76-098, Duluth Environmental Research Laboratory, Duluth, MN (1976).

Bryan, G. W.: Some aspects of heavy metal tolerance in aquatic organisms. In A. P. M. Lockwood (ed.): Effects of pollutants on aquatic organisms. New York: Cambridge University Press (1976).

Buckley, J. A., C. M. Whitmore, and R. I. Matsuda: Changes in blood chemistry and blood cell morphology in coho salmon (*Oncorhynchus kisutch*) following exposure to sublethal levels of total residual chlorine in municipal wastewater. J. Fish. Res. Board Can. **33**, 776 (1976).

Bull, C. J., and J. E. McInerney: Behavior of juvenile coho salmon (*Oncorhynchus kisutch*) exposed to Sumithion (fenitrothion), an organophosphate insecticide. J. Fish. Res. Board Can. **31**, 1867 (1974).

Cairns, J., Jr.: Biological monitoring part VI–Future needs. Water Res. **15**, 941 (1981).

_____, and W. H. van der Shalie: Biological monitoring. Part I–Early warning systems. Water Res. **14**, 1179 (1980).

Cairns, M. A., R. R. Garton, and R. A. Tubb: Use of fish ventilation frequency to estimate chronically safe toxicant concentrations. Trans. Amer. Fish. Soc. **111**, 70 (1982).

Calamari, D., R. Marchetti, and G. Vailati: Influence of water hardness on cadmium toxicity to *Salmo gairdneri* Rich. Water Res. **14**, 1421 (1980).

Camp, B. J., E. Hejtmancik, C. Armour, and D. H. Lewis: Acute effects of Aroclor® 1254 (PCB) on *Ictalurus punctatus* (catfish). Bull. Environ. Contam. Toxicol. **12**, 204 (1974).

Chapman, G. A.: Toxicities of cadmium copper and zinc to four juvenile life stages of chinook salmon and steelhead. Trans. Amer. Fish. Soc. **107**, 841 (1978).

Cherry, D. S., and J. Cairns, Jr.: Biological monitoring: Part V–Preference and avoidance studies. Water Res. **16**, 263 (1982).

_____, S. R. Larrick, K. L. Dickson, R. C. Hoehn, and J. Cairns, Jr.: Significance of hypochlorous acid in free residual chlorine to the avoidance response of spotted bass (*Micropterus punctulatus*) and rosyface shiner (*Notropis rubellus*). J. Fish. Res. Board Can. **34**, 1365 (1977 a).

_____ _____, J. D. Giattina, K. L. Dickson, and J. Cairns, Jr.: The avoidance response of the common shiner to total and combined residual chlorine in thermally influenced discharges. In: Energy and environmental stress in aquatic systems. Savannah River Ecology Laboratory, Aiken, SC (1978).

_____ _____ _____ _____ _____ Avoidance and toxicity responses of fish to intermittent chlorination. Environ. Internat. **2**, 85 (1979).

_____ _____ _____, J. Cairns, Jr., and J. Van Hassel: Influence of temperature selection upon the chlorine avoidance of cold and warmwater fish. Can. J. Fish. Aq. Sci. **39**, 162 (1982).

_____, R. C. Hoehn, S. S. Waldo, D. H. Willis, J. Cairns, Jr., and K. L. Dickson: Field-laboratory determined avoidances of the spotfin shiner and the bluntnose minnow to chlorinated discharges. Water Res. Bull. **13**, 1047 (1977 b).

Christensen, G. M.: Effects of metal cations and other chemicals upon the *in vitro* activity of two enzymes in the blood plasma of the white sucker, *Catostomus commersoni* (Lacepede). Chem.-Biol. Interactions **4**, 351 (1972).

_____, and B. Riedel: Effect of water pollutants and other chemicals upon the activity of lipase *in vitro*. Arch. Environ. Contam. Toxicol. **10**, 357 (1981).

_____, E. Hunt, and J. Fiandt: The effect of methylmercuric chloride, cadmium chloride, and lead nitrate on six biochemical factors of the brook trout (*Salvelinus fontinalis*). Toxicol. Applied Pharmacol. **42**, 523 (1977).

Cope, O. B., E. M. Wood, and G. H. Wallen: Some chronic effects of 2,4-D on the bluegill (*Lepomis macrochirus*). Trans. Amer. Fish. Soc. **99**, 1 (1970).

Costa, H. H.: Responses of *Gammarus pulex* (L.) to modified environment. I. Reactions to toxic solutions. Crustaceana **11**, 245 (1966).

Cripe, C. R.: An automated device (AGARS) for studying avoidance of pollutant gradients by aquatic organisms. J. Fish. Res. Board Can. **36**, 11 (1979).

_____, J. H. Cripe, and R. J. Livingston: Apparatus for the quantitative determination of locomotor activity patterns of aquatic organisms using infrared light-emitting diodes. J. Fish. Res. Board Can. **32**, 1884 (1975).

Dandy, J. W. T.: Activity response to chlorine in the brook trout, *Salvelinus fontinalis* (Mitchell). Can. J. Zool. **50**, 405 (1972).

Davey, R. B., M. V. Meisch, and F. L. Carter: Toxicity of five rice field pesticides to the mosquitofish, *Gambusia affinis* and green sunfish, *Lepomis cyanellus* under laboratory and field conditions in Arkansas. Environ. Entomol. **5**, 1053 (1976).

Davies, P. H., J. P. Goettl, Jr., J. R. Sinley, and N. F. Smith: Acute and chronic toxicity of lead to rainbow trout, *Salmo gairdneri*, in hard and soft water. Water Res. **10**, 199 (1976).

Davis, P. W., J. M. Friedhoff, and G. A. Wedemeyer: Organochlorine insecticide, herbicide, and polychlorinated biphenyl (PCB) inhibition of NaK-ATPase in rainbow trout. Bull. Environ. Contam. Toxicol. **8**, 69 (1972).

Davy, F. B., H. Kleerekoper, and P. Gensler: Effects of exposure to sublethal DDT on the locomotor behavior of the goldfish (*Carassius auratus*). J. Fish. Res. Board Can. **29**, 1333 (1972).

_____ _____, and J. H. Matis: Effects of exposure to sublethal DDT on the exploratory behavior of goldfish (*Carassius auratus*). Water Resources Res. **9**, 900 (1973).

Dawson, M. A., E. Gould, F. T. Thurberg, and A. Calabrese: Physiological response of juvenile striped bass, *Morone saxatilis*, to low levels of cadmium and mercury. Ches. Sci. **18**, 353 (1977).

DeFoe, D. L., G. D. Veith, and R. W. Carlson: Effects of Aroclor® 1248 and 1260 on the fathead minnow (*Pimephales promelas*). J. Fish. Res. Board Can. **35**, 997 (1978).

Degraeve, G. M., W. J. Blogoslawski, W. A. Brings, J. A. Fava, B. J. Finlayson, T. P. Frost, T. M. Krischan, J. W. Meldrim, D. T. Michaud, R. D. Nakatani, and G. L. Seegert: Chlorine. In R. V. Thurston, R. C. Russo, C. M. Fetterolf, Jr., T. A. Edsall, and Y. M. Barber, Jr. (eds.): A review of the EPA redbook: Quality criteria for water. Water Quality Section, American Fisheries Society, Bethesda, MD (1979).

Desaiah, D., L. K. Cutkomp, R. B. Koch, and A. Jarvinen: DDT: effect of continuous exposure on ATPase activity in fish, *Pimephales promelas*. Arch. Environ. Contam. Toxicol. **3**, 132 (1975).

Dill, P. A., and R. C. Saunders: Retarded behavioral development and impaired balance in Atlantic salmon (*Salmo salar*) alevins hatched from gastrulae exposed to DDT. J. Fish. Res. Board Can. **31**, 1936 (1974).

Dodson, J. J., and C. I. Mayfield: The dynamics and behavioral toxicology of Aqua-Kleen® (2,4-D butoxyethanol ester) as revealed by the modification of rheotropism in rainbow trout. Trans. Amer. Fish. Soc. **108**, 632 (1979 a).

_____ _____ Modification of the rheotropic response of rainbow trout (*Salmo gairdneri*) by sublethal doses of the aquatic herbicides diquat and simazine. Environ. Pollut. **18**, 147 (1979 b).

Domanik, A. M., and J. H. Zar: The effect of malathion on the temperature selection response of the common shiner, *Notropis cornutus* (Mitchell). Arch Environ. Contam. Toxicol. **7**, 193 (1978).

Drummond, R. A., G. F. Olson, and A. R. Batterman: Cough response and uptake of mercury by brook trout, *Salvelinus fontinalis*, exposed to mercuric compounds at different hydrogen-ion concentrations. Trans. Amer. Fish. Soc. **103**, 244 (1974).

_____, W. A. Spoor, and G. F. Olson: Some short-term indicators of sublethal effects of copper on brook trout, *Salvelinus fontinalis*. J. Fish. Res. Board Can. **30**, 698 (1973).

Eaton, J. G., J. M. McKim, and G. W. Holcombe: Metal toxicity to embryos and larvae of seven freshwater fish species—I. Cadmium. Bull. Environ. Contam. Toxicol. **19**, 95 (1978).

Eidt, D. C.: The effect of fenitrothion from large-scale forest spraying on benthos in New Brunswick headwater streams. Can. Entomologist **107**, 743 (1975).

Ellgaard, E. G., J. C. Ochsner, and J. K. Cox: Locomotor hyperactivity induced in the bluegill sunfish, *Lepomis macrochirus*, by sublethal concentrations of DDT. Can. J. Zool. **55**, 1077 (1977).

_____, J. E. Tusa, and A. A. Malizia: Locomotor activity of the bluegill, *Lepomis macrochirus*: Hyperactivity induced by sublethal concentrations of cadmium, chromium, and zinc. J. Fish. Biol. **12**, 19 (1973).

Farr, J. A.: Impairment of antipredator behavior in *Palaemonetes pugio* by exposure to sublethal doses of parathion. Trans. Amer. Fish. Soc. **106**, 287 (1977).

_____ The effects of methyl parathion on predator choice of two estuarine prey species. Trans. Amer. Fish. Soc. **107**, 87 (1978).

Faust, S. D., and M. Gomaa: Chemical hydrolysis of some organic phosphorus and carbamate pesticides in aquatic environments. Environ. Lett. **3**, 171 (1972).

Fava, J. A., Jr., and C. Tsai: Immediate behavioral reactions of blacknose dace, *Rhinichthys atratulus*, to domestic sewage and its toxic constituents. Trans. Amer. Fish. Soc. **105**, 430 (1976).

_____ _____ Delayed behavioral responses of the blacknose dace (*Rhinichthys atratulus*) to chloramines and free chlorine. Comp. Biochem. Physiol. **60C**, 123 (1978).

Fingerman, S. W., and L. C. Russell: Effects of the polychlorinated biphenyl Aroclor 1242 on locomotor activity and on the neurotransmitters dopamine and norepinephrine in the brain of the gulf killifish, *Fundulus grandis*. Bull. Environ. Contam. Toxicol. **25**, 682 (1980).

Folmar, L. C.: Overt avoidance reaction of rainbow trout fry to nine herbicides. Bull. Environ. Contam. Toxicol. **15**, 509 (1976).

_____ Avoidance chamber responses of mayfly nymphs exposed to eight herbicides. Bull. Environ. Contam. Toxicol. **19**, 312 (1978).

Freedman, M. L., P. M. Cunningham, J. E. Schindler, and M. J. Zimmerman: Effect of lead speciation on toxicity. Bull. Environ. Contam. Toxicol. **25**, 389 (1980).

Gardner, D. R.: The effect of some DDT and methoxychlor analogs on temperature selection and lethality in brook trout fingerlings. Pest. Biochem. Physiol. **2**, 437 (1973).

Geckler, J. R., W. B. Horning, T. M. Neiheisel, Q. H. Pickering, E. L. Robinson, and C. E. Stephan: Validity of laboratory tests for predicting copper toxicity in streams. U.S. Environmental Protection Agency, EPA-600/3-76-116, Environmental Research Laboratory, Duluth, MN (1976).

Giattina, J. D., D. S. Cherry, S. R. Larrick, and J. Cairns, Jr.: Comparison of laboratory and field avoidance behavior of fish in heated chlorinated water. Trans. Amer. Fish. Soc. **110**, 526 (1981).

_____, R. R. Garton, and D. G. Stevens: The avoidance of copper and nickel by rainbow trout as monitored by a computer-based data acquisition system. Trans. Amer. Fish. Soc., **111**, 491 (1982).

Grieve, J. A., L. E. Johnston, T. G. Dunstall, and J. Minor: A program to introduce site-specific chlorinated regimes at Ontario Hydro generating stations. In R. L. Jolley, H. Gorchey, and D. H. Hamilton, Jr. (eds.): Water chlorination: Environmental impact and health effects. Ann Arbor: Ann Arbor Science Publishers (1978).

Hale, J. G.: Toxicity of metal mining wastes. Bull. Contam. Toxicol. **17**, 66 (1977).

Hall, J. W., J. C. Arnold, W. T. Waller, and J. Cairns, Jr.: A procedure for the detection of pollution by fish movements. Biometrics **31**, 11 (1975).

Halter, M. T., and H. E. Johnson: Acute toxicities of a polychlorinated biphenyl (PCB) and DDT alone and in combination to early life stages of coho salmon (*Oncorhynchus kisutch*). J. Fish. Res. Board Can. **31**, 1543 (1974).

Hansen, D. J.: DDT and malathion: effect on salinity selection by mosquitofish. Trans. Amer. Fish. Soc. **101**, 346 (1972).

_____ Avoidance of pesticides by untrained sheepshead minnows. Trans. Amer. Fish. Soc. **98**, 426 (1969).

_____, S. C. Schimmel, and J. Forester: Effects of Aroclor® 1016 on embryos, fry, juveniles, and adults of sheepshead minnows (*Cyprinodon variegatus*). Trans. Amer. Fish. Soc. **104**, 584 (1975).

_____, E. Matthews, S. L. Nall, and D. P. Dumas: Avoidance of pesticides by untrained mosquitofish, *Gambusia affinis*. Bull. Environ. Contam. Toxicol. **8**, 46 (1973 a).

_____, P. R. Parrish, J. I. Lowe, A. J. Wilson, Jr., and P. D. Wilson: Chronic toxicity, uptake, and retention of Aroclor® 1254 in two estuarine fishes. Bull. Environ. Contam. Toxicol. **6**, 113 (1971).

_____, S. C. Schimmel, and J. M. Keltner, Jr.: Avoidance of pesticides by grass shrimp (*Palaemonetes pugio*). Bull. Environ. Contam. Toxicol. **9**, 129 (1973 b).

_____ _____, and E. Matthews: Avoidance of Aroclor® 1254 by shrimp and fishes. Bull. Environ. Contam. Toxicol. **12**, 253 (1974).

Hara, T. J.: Electrical responses of the olfactory bulb of Pacific salmon *Oncorhynchus nerka* and *Oncorhynchus kisutch*. J. Fish. Res. Board Can. **29**, 1351 (1972).

_____, Y. M. C. Law, and S. McDonald: Effects of mercury and copper on the olfactory response in rainbow trout (*Salmo gairdneri*). J. Fish. Res. Board Can. **33**, 1568 (1976).

Hasler, A. D., and W. J. Wisby: Use of fish for the olfactory assay of pollutants (phenols) in water. Trans. Amer. Fish. Soc. **79**, 64 (1950).

Hatfield, C. T., and J. M. Anderson: Effects of two insecticides on the vulnerability of Atlantic salmon (*Salmo salar*) parr to brook trout (*Salvelinus fontinalis*) predation. J. Fish. Res. Board Can. **29**, 27 (1972).

_____, and P. H. Johansen: Effects of four insecticides on the ability of Atlantic salmon parr (*Salmo salar*) parr to learn and return a simple conditioned response. J. Fish. Res. Board Can. **29**, 315 (1972).

Heath, A. G.: Toxicity of intermittent chlorination to freshwater fish: Influence of temperature and chlorine form. Hydrobiologia **56**, 39 (1977).

Henderson, C., and Q. H. Pickering: Toxicity of organic phosphorus insecticides to fish. Trans. Amer. Fish. Soc. **87**, 39 (1958).

Hiatt, R. W., J. J. Naughton, and D. C. Matthews: Effects of chemicals on a schooling fish, *Kuhlia sandvicensis*. Biol. Bull. **104**, 28 (1953).

Hochachka, P. W., and G. N. Somero: Strategies of biochemical adaptation. Philadelphia: W. B. Saunders (1973).

Hodson, P. V., B. R. Blunt, and D. J. Spry: Chronic toxicity of water-borne and dietary lead to rainbow trout (*Salmo gairdneri*) in Lake Ontario water. Water Res. **12**, 869 (1978).

_____ _____ _____, and K. Austen: Evaluation of erythrocyte δ-amino levulinic acid dehydratase activity as a short-term indicator in fish of a harmful exposure to lead. J. Fish. Res. Board Can. **34**, 501 (1977).

Holland, E. A.: Chlorine and chloramine experiments. Washington, D.C.: Dept. Fish. Res. Bull. No. 5, 188 (1960).

Holland, H. T., and J. I. Lowe: Malathion: chronic effects on estuarine fish. Mosquito News **26**, 383 (1966).

Holcombe, G. W., D. A. Benoit, E. N. Leonard, and J. M. McKim: Long-term effects of lead exposure on three generations of brook trout (*Salvelinus fontinalis*). J. Fish. Res. Board Can. **33**, 1731 (1976).

Hose, J. E., and R. J. Stoffel: Avoidance response of juvenile *Chromis punctipinnis* to chlorinated seawater. Bull. Environ. Contam. Toxicol. **25**, 929 (1980).

Ishio, S.: Behavior of fish exposed to toxic substances, pp. 19-40. In Advances in water pollution research. Proc. 2nd Internat. Conf. Water Poll. Res., Tokyo. London: Pergamon Press (1965).

Jackson, D. A., J. M. Anderson, and D. R. Gardner: Further investigation of the effect of DDT on learning in fish. Can. J. Zool. **48**, 577 (1970).

Jarvinen, A. W., and D. K. Tanner: Toxicity of selected control release and corresponding unformulated technical grade pesticides to the fathead minnow *Pimephales promelas*. Environ. Pollut. **27**, 179 (1982).

_____, M. J. Hoffman, and T. W. Thorlsund: Long-term toxic effects of DDT food and water exposure on fathead minnows (*Pimephales promelas*). J. Fish. Res. Board Can. **34**, 2089 (1977).

Jones, B. F., C. E. Warren, C. E. Bond, and P. Doudoroff: Avoidance reactions of salmonid fishes to pulp mill effluents. Sewage & Ind. Wastes **28**, 1403 (1956).

Jones, J. R. E.: The reactions of *Pygosteus pungitius* L. to toxic solutions. J. Exp. Biol. **24**, 110 (1947).

_____ A further study of the reactions of fish to toxic solutions. J. Exp. Biol. **25**, 22 (1948).

_____ The reactions of the minnow, *Phoxinus phoxinus* (L.) to solutions of phenol, ortho-cresol, and para cresol. J. Exp. Biol. **28**, 261 (1951).

Kania, H. J., and J. O'Hara: Behavioral alterations in a simple predator-prey system due to sublethal exposure to mercury. Trans. Amer. Fish. Soc. **103**, 134 (1974).

Kelso, J. R. M.: Density, distribution, and movement of Nipigon Bay fishes in relation to a pulp and paper mill effluent. J. Fish. Res. Board Can. **34**, 879 (1977).

Kleerekoper, H., J. B. Waxman, and J. Matis: Interactions of temperature and copper ions as orienting stimuli in the locomotor behavior of the goldfish (*Carrassius auratus*). J. Fish. Res. Board Can. **30**, 725 (1973).

Kleerekoper, H., J. F. Westlake, J. H. Matis, and P. J. Gensler: Orientation of goldfish (*Carrassius auratus*) in response to a shallow gradient of a sublethal concentration of copper in an open field. J. Fish. Res. Board Can. **29**, 44 (1972).

Koch, R. B., D. Desaiah, H. H. Yap, and L. K. Cutkomp: Polychlorinated biphenyls: effect of long-term exposure on ATPase activity in fish, *Pimephales promelas*. Bull. Environ. Contam. Toxicol. **7**, 87 (1972).

Kynard, B.: Avoidance behavior of insecticide susceptible and resistant populations of mosquitofish to four insecticides. Trans. Amer. Fish. Soc. **103**, 557 (1974).

Larrick, S. R., K. L. Dickson, D. S. Cherry, and J. Cairns, Jr.: Determining fish avoidance of polluted water. Hydrobiologia **61**, 257 (1978).

Larsson, A., B. Bengtsson, and O. Svanberg: Some haematological and biochemical effects of cadmium on fish. In A. P. M. Lockwood (ed.): Effects of pollutants on aquatic organisms. New York: Cambridge University Press (1976).

Lewis, F. G., III, and R. J. Livingston: Avoidance of bleached kraft pulp mill effluent by pinfish (*Lagodon rhomboides*) and gulf killifish (*Fundulus grandis*). J. Fish. Res. Board Can. **34**, 568 (1977).

Lindahl, P. E., and E. Schwanbom: A method for the detection and quantitative estimation of sublethal poisoning in living fish. Oikos **22**, 210 (1971).

Livingston, R. J.: Review of current literature concerning the acute and chronic effects of pesticides on aquatic organisms. CRC Critical Reviews in Environmental Control , 325 (1977).

_____, C. R. Cripe, R. A. Laughlin, and F. G. Lewis, III; Avoidance responses of esturaine organisms to storm water runoff and pulp mill effluents, pp. 313-331. In M. Wiley (ed.): Estuarine processes, Vol. 1. Uses, stresses, and adaptations to the estuary. New York: Academic Press (1976).

Lockhart, W. L., D. A. Metner, and N. Grift: Biochemical and residue studies on rainbow trout (*Salmo gairdneri*) following field and laboratory exposures to fenitrothion. Manit. Entomol. **7**, 26 (1973).

Lunn, C. R., D. P. Toews, and D. J. Pree: Effects of three pesticides on respiration, coughing, and heart rates of rainbow trout (*Salmo gairdneri* Richardson). Can. J. Zool. **54**, 214 (1976).

Lyons, D. B., C. H. Buckner, B. B. McLeod, and K. M. S. Sundaram: The effects of fenitrothion, metacil® and orthene® on frog larvae. Chemical Control Research Institute, Rept. CC-X-129, Ottawa, Ontario (1976).

Macek, K. J., C. Hutchinson, and O. B. Cope: The effects of temperature on the susceptibility of bluegills and rainbow trout to selected pesticides. Bull. Environ. Contam. Toxicol. **4**, 174 (1969).

Maciorowski, H. D., R. McV. Clarke, and E. Scherer: The use of avoidance-preference bioassays with aquatic invertebrates. Environmental Protection Service Report, EPS-5AR-77-1, Halifax, Canada (1977).

Macleod, J. C., and E. Pessah: Temperature effects on mercury accumulation, toxicity, and metabolic rate in rainbow trout (*Salmo gairdneri*). J. Fish. Res. Board Can. **30**, 485 (1973).

Marcstrom, A.: Reaction thresholds of roaches (*Leuciscus rutilus* L.) to some aromatic substances. Arkiv. for Zoologi **24**, 335 (1959).

Marcucella, H., and C. I. Abramson: Behavioral toxicology and teleost fish. In D. I. Mostofsky (ed.): The behavior of fish and other aquatic animals. New York: Academic Press (1978).

Mattice, J. S., and H. E. Zittel: Site-specific evaluation of power plant chlorination. J. Water Poll. Contr. Fed. **40**, 2284 (1976).

_____, S. C. Tsai, and M. B. Burch: Comparative toxicity of hypochlorous acid and hypochlorite ions to mosquitofish. Trans. Amer. Fish. Soc. **110**, 519 (1981).

Mauck, W. L., P. M. Mehrle, and F. L. Mayer: Effects of the polychlorinated biphenyl Aroclor® 1254 on growth, survival, and bone development in brook trout (*Salvelinus fontinalis*). J. Fish. Res. Board Can. **35**, 1084 (1978).

McCrady, J. K., and G. A. Chapman: Determination of copper complexing capacity of natural river water, well water, and artificially reconstituted water. Water Res. **13**, 143 (1979).

McKim, J. M., and D. A. Benoit: Effects of long-term exposures to copper on survival, growth, and reproduction of brook trout (*Salvelinus fontinalis*). J. Fish. Res. Board Can. **28**, 655 (1971).

_____, G. M. Christensen, and E. P. Hunt: Change in the blood of brook trout (*Salvelinus fontinalis*) after short-term and long-term exposure to copper. J. Fish. Res. Board Can. **27**, 1883 (1970).

_____, J. G. Eaton, and G. W. Holcombe: Metal toxicity to embryos and larvae of eight species of freshwater fish–II: Copper. Bull. Environ. Contam. Toxicol. **19**, 608 (1978).

_____, G. F. Olson, G. W. Holcombe, and E. P. Hunt: Long-term effects of methylmercuric chloride on three generations of brook trout (*Salvelinus fontinalis*): toxicity, accumulation, distribution, and elimination. J. Fish. Res. Board Can. **33**, 2726 (1976).

McLeay, D. J.: Development of a blood sugar bioassay for rapidly measuring stressful levels of pulp mill effluents to salmonid fish. J. Fish. Res. Board Can. **34**, 477 (1977).

_____, and D. A. Brown: Stress and chronic effects of untreated and treated kraft pulp mill effluent on the biochemistry and stamina of juvenile coho salmon (*Oncorhynchus kisutch*). J. Fish. Res. Board Can. **36**, 1049 (1979).

Meffert, P.: Ultrasonic recorder for locomotor activity studies. Trans. Amer. Fish. Soc. **97**, 12 (1968).

Meehan, W. R., L. A. Norris, and H. S. Sears: Toxicity of various formulations of 2,4-D to salmonids in southeast Alaska. J. Fish. Res. Board Can. **31**, 480 (1974).

Meldrim, J. W., and J. A. Fava, Jr.: Behavioral avoidance responses of estuarine fishes to chlorine. Ches. Sci. **18**, 1[illegible]4 (1977).

_____, J. J. Gift, and B. R. Petrosky: The effect of temperature and chemical pollutants on the behavior of several estuarine organisms. Icthyological Assoc., Inc. Bull. 11. Available from NTIS as PB 239 347 (1974).

Middaugh, D. P., J. A. Couch, and A. M. Crane: Responses of early life history stages of the striped bass, *Morone saxatilis*, to chlorination. Ches. Sci. **18**, 141 (1977).

Miller, D. L., and D. M. Ogilvie: Temperature selection in brook trout (*Salvelinus fontinalis*) following exposure to DDT, PCB, or phenol. Bull. Environ. Contam. Toxicol. **14**, 545 (1975).

Moffett, G. B., and J. D. Yarbrough: The effects of DDT, toxaphene, and dieldrin on succinic and dehydrogenase activity in insecticide-resistant and susceptible *Gambusia affinis*. J. Agr. Food Chem. **20**, 558 (1972).

Mount, D. I., and C. E. Stephan: A method for establishing acceptable toxicant limits for fish—Malathion and butoxy-ethanol ester of 2,4-D. Trans. Amer. Fish. Soc. **96**, 185 (1967).

Mulla, M. S., and L. S. Mian: Biological and environmental impacts of the insecticides malathion and parathion on nontarget biota in aquatic ecosystems. Residue Reviews **78**, 101 (1981).

Nebeker, A. V., F. A. Puglisi, and D. L. DeFoe: Effect of polychlorinated biphenyl compounds on survival and reproduction of the fathead minnow and flagfish. Trans. Amer. Fish. Soc. **103**, 562 (1974).

_____, C. Savonen, and D. G. Stevens: Sensitivity of rainbow trout early life stages to nickel chloride. Manuscript to be submitted Arch. Environ. Contam. Toxicol. (1982).

Nieboer, E., and D. H. S. Richardson: The replacement of the nondescript term "heavy metals" by a biologically and chemically significant classification of metal ions. Environm. Poll. **1**, 3 (1980).

Ogilvie, D. M., and J. M. Anderson: Effect of DDT on temperature selection by young Atlantic salmon, *Salmo salar*. J. Fish. Res. Board Can. **22**, 503 (1965).

_____, and D. L. Miller: Duration of a DDT-induced shift in the selected temperature of Atlantic salmon, *Salmo salar*. Bull. Environ. Contam. Toxicol. **18**, 86 (1976).

Osborne, L. L., D. R. Iredale, F. J. Wrona, and R. W. Davies: Effects of chlorinated sewage effluent on fish in the Sheep River, Alberta. Trans. Amer. Fish. Soc. **110**, 536 (1981).

Peterson, R. H.: Temperature selection of Atlantic salmon (*Salmo salar*) and brook trout (*Salvelinus fontinalis*) as influenced by various chlorinated

hydrocarbons. J. Fish. Res. Board Can. **30**, 1091 (1973).

_____ Influence of fenitrothion on swimming velocities of brook trout (*Salvelinus fontinalis*). J. Fish. Res. Board Can. **31**, 1757 (1974).

_____ Temperature selection of juvenile Atlantic salmon (*Salmo salar*) as influenced by various toxic substances. J. Fish. Res. Board Can. **33**, 1722 (1976).

Pickering, Q. H.: Chronic toxicity of nickel to the fathead minnow. J. Water Poll. Contr. Fed. **46**, 760 (1974).

_____, and M. H. Gast: Acute and chronic toxicity of cadmium to the fathead minnow (*Pimephales promelas*). J. Fish. Res. Board Can. **29**, 1099 (1972).

_____, and C. Henderson: The acute toxicity of some heavy metals to different species of warmwater fishes. Air Water Pollut. Internat. J. **10**, 453 (1966).

_____ _____, and A. E. Lemke: The toxicity of organic phosphorus insecticides to different species of warmwater fishes. Trans. Amer. Fish. Soc. **91**, 175 (1962).

Post, G., and R. A. Leasure: Sublethal effect of malathion to three salmonid species. Bull. Environ. Contam. Toxicol. **12**, 312 (1974).

_____, and T. R. Schroeder: The toxicity of four insecticides to four salmonid species. Bull. Environ. Contam. Toxicol. **6**, 144 (1971).

Pruell, R. J., and F. R. Engelhardt: Liver cadmium uptake, catalase inhibition, and cadmium thionein production in the killifish (*Fundulus heteroclitus*) induced by experimental cadmium exposure. Marine Environ. Res. **3**, 101 (1980).

Rand, G. M.: The effect of exposure to a subacute concentration of parathion on the general locomotor behavior of the goldfish. Bull. Environ. Contam. Toxicol. **18**, 259 (1977).

_____, H. Kleerekoper, and J. Matis: Interaction of odour and flow perception and the effects of parathion in the locomotor orientation of the goldfish, *Carassius auratus* L. J. Fish Biol. **7**, 497 (1975).

Roch, M., and E. J. Maly: Relationship of a cadmium-induced hypocalcemia with mortality in rainbow trout (*Salmo gairdneri*) and the influence of temperature on toxicity. J. Fish. Res. Board Can. **36**, 1297 (1979).

Sanders, H. O.: Toxicities of some herbicides to six species of freshwater crustaceans. J. Water. Poll. Control Fred. **42**, 1544 (1970).

Saunders, R. L., and J. B. Sprague: Effects of copper-zinc mining pollution on a spawning migration of Atlantic salmon. Water Res. **1**, 419 (1967).

Sauter, S., K. S. Buxton, K. J. Macek, and S. R. Petrocelli: Effects of exposure to heavy metals on selected freshwater fish–Toxicity of copper, cadmium, chromium, and lead to eggs and fry of seven fish species. U.S. Environmental Protection Agency, EPA-600/3-76-105, Cincinnati, OH (1976).

Sawyer, C. N., and P. M. McCarty: Chemistry for sanitary engineers. New York: McGraw-Hill (1967).

Schaumberg, F. D., T. E. Howard, and C. C. Walden: A method to evaluate the effects of water pollutants on fish respiration. Water Res. **1**, 731 (1967).

Scherer, E.: Avoidance of fenitrothion by goldfish (*Carassius auratus*). Bull. Environ. Contam. Toxicol. **13**, 492 (1975).

_____ Behavioural assays–Principles, results, and problems. Environmental Protection Service, Techn. Rept. EPA-5AR-77-1. Halifax, Canada (1977).

_____, S. H. Nowak, S. E. Harrison, and D. L. Kripiakevich: Testing locomotor activity responses with ultrasonic beams. In E. Scherer (ed.): Toxicity tests for freshwater organisms. Canadian Special Publication of Fisheries and Aquatic Sciences. Winnipeg, Manitoba, Canada (1979).

Schimmel, S. C., D. J. Hansen, and J. Forester: Effects of Aroclor® 1254 on laboratory-reared embryos and fry of sheepshead minnows (*Cyprinodon variegatus*). Trans. Amer. Fish. Soc. **103**, 582 (1974).

Schneider, M. J., S. A. Barraclough, R. G. Genoway, and M. L. Wolford: Effects of phenol on predation of juvenile rainbow trout, *Salmo gairdneri*. Environm. Poll. **23**, 121 (1980).

Schreck, C. B., and H. W. Lorz: Stress response of coho salmon (*Oncorhynchus kisutch*) elicited by cadmium and copper and potential use of cortisol as an indicator of stress. J. Fish. Res. Board Can. **35**, 1124 (1978).

Seim, W. K., J. A. Lichatowich, R. H. Ellis, and G. E. Davis: Effects of kraft mill effluents on juvenile salmon production in laboratory streams. Water Res. **11**, 189 (1977).

Sellers, C. M., Jr., A. G. Heath, and M. L. Bass: The effect of sublethal concentrations of copper and zinc on ventilatory activity, blood oxygen, and pH in rainbow trout (*Salmo gairdneri*). Water Res. **9**, 401 (1975).

Shirer, H. W., J. Cairns, Jr., and W. T. Waller: A simple apparatus for measuring activity patterns of fishes. Water Resources Bull. **103**, 582 (1974).

Sinley, J. R., J. P. Goettl, Jr., and P. H. Davies: The effects of zinc on rainbow trout (*Salmo gairdneri*) in hard and soft water. Bull. Environ. Contam. Toxicol. **12**, 193 (1974).

Smith, W. E., and R. W. Saalfield: Studies on Columbia River smelt, *Thaleichthys pacificus* (Richardson). Wash. Dept. Fisheries Res. Paper 1, p. 1 (1955).

Sparks, R. E., J. Cairns, Jr., and A. G. Heath: The use of bluegill breathing rates to detect zinc. Water Res. **6**, 895 (1972).

Spehar, R. L.: Cadmium and zinc toxicity to flagfish, *Jordanella floridae*. J. Fish. Res. Board Can. **33**, 1939 (1976).

_____, E. N. Leonard, and D. L. DeFoe: Chronic effects of cadmium and zinc mixtures on flagfish (*Jordanella floridae*). Trans. Amer. Fish. Soc. **107**, 354 (1978).

Sprague, J. B.: Avoidance of copper-zinc solutions by young salmon in the laboratory. J. Water Pol. Control Fed. **36**, 990 (1964 a).

_____ Lethal concentrations of copper and zinc for young Atlantic salmon. J. Fish. Res. Board Can. **21**, 17 (1964 b).

_____ Avoidance reaction of rainbow trout to zinc sulfate solutions. Water Res. **2**, 367 (1968).

_____, and D. E. Drury: Avoidance reactions of salmonid fish to representative pollutants, pp. 169-179. In S. H. Jenkins (ed.): Advances in water pollution research. New York: Pergamon Press (1969).

_____, P. F. Elson, and R. L. Saunders: Sublethal copper-zinc pollution in a salmon river—A field and laboratory study. Internat. J. Air. Water Poll. **9**, 531 (1965).

Stober, Q. J., P. A. Dinnel, E. F. Hurlburt, and D. H. DiJulio: Acute toxicity and

behavioral responses of coho salmon (*Oncorhynchus kisutch*) and shiner perch (*Cymatogaster aggregata*) to chlorine in heated seawater. Water Res. **14**, 347 (1980).

Stott, B., and B. R. Buckley: Avoidance experiments with homing shoals of minnows, *Phoxinus phoxinus*, in a laboratory stream channel. J. Fish. Biol. **14**, 135 (1979).

Sullivan, J. F., G. J. Atchison, D. J. Kolar, and A. W. McIntosh: Changes in the predator-prey behavior of fathead minnows (*Pimephales promelas*) and largemouth bass (*Micropterus salmoides*) caused by cadmium. J. Fish. Res. Board Can. **35**, 446 (1978).

Summerfelt, R. C., and W. M. Lewis. 1967. Repulsion of green sunfish by certain chemicals. J. Water. Poll. Control Fed. **39**, 2030 (1967).

Sutterlin, A. M.: Pollutants and the chemical senses of aquatic animals–Perspective and review. Chemical Senses and Flavor **1**, 167 (1974).

Sutterlin, A. M., and R. Gray: Chemical basis for homing of Atlantic salmon (*Salmo salar*) to a hatchery. J. Fish. Res. Board Can. **30**, 985 (1973).

Symons, P. E. K.: Behavior of young Atlantic salmon (*Salmo salar*) exposed to or force-fed fenitrothion, an organophosphate insecticide. J. Fish. Res. Board Can. **30**, 651 (1973).

_____ Dispersal and toxicology of the insecticide fenitrothion; predicting hazards of forest spraying. Residue Reviews **68**, 1 (1977).

Thatcher, T. O.: The relative sensitivity of Pacific northwest fishes and invertebrates to chlorinated seawater. In R. L. Jolley, H. Gorchey, and D. H. Hamilton, Jr. (eds.): Water chlorination: Environmental impact and health effects, Vol. II. Ann Arbor: Ann Arbor Sci. Publ. (1978).

Timms, A. M., H. Kleerekoper, and J. Matis: Locomotor response of goldfish, channel catfish, and largemouth bass to a "copper-polluted" mass of water in an open field. Water Resources Res. **8**, 1574 (1972).

Travis, T. W., and R. G. Heath: Some physiological responses of rainbow trout (*Salmo gairdneri*) to intermittent monochloramine exposure. Water Res. **15**, 977 (1981).

Tsai, C.: Water quality and fish life below sewage outfalls. Trans. Amer. Fish. Soc. **102**, 281 (1973).

Tucker, R. K., and J. S. Leitzke: Comparative toxicology of insecticides for vertebrate wildlife and fish. Pharmaceut. Ther. **6**, 167 (1979).

USEPA (*United States Environmental Protection Agency*): Quality criteria for water–Red Book. U.S. Environmental Protection Agency, Office of Water and Hazardous Materials, Washington, D.C. (1976).

_____ Ambient water quality criteria for zinc. U.S. Environmental Protection Agency, EPA-400/5-80-079, Environmental Criteria and Assessment Office, Cincinnati, OH (1980 a).

_____ Ambient water quality criteria for mercury. U.S. Environmental Protection Agency, EPA-400/5-80-058, Environmental Criteria and Assessment Office, Cincinnati, OH (1980 b).

_____ Ambient water quality criteria for cadmium. U.S. Environmental Protection Agency, EPA-400/5-80-025, Environmental Criteria and Assessment Office, Cincinnati, OH (1980 c).

_____ Ambient water quality criteria for nickel. U.S. Environmental Protection Agency, EPA-400/5-80-060, Environmental Criteria and Assessment Office, Cincinnati, OH (1980 d).

_____ Ambient water quality criteria for lead. U.S. Environmental Protection Agency, EPA-400/5-80-057, Environmental Criteria and Assessment Office, Cincinnati, OH (1980 e).

_____ Ambient water quality criteria for phenol. U.S. Environmental Protection Agency, EPA-400/5-80-066, Environmental Criteria and Assessment Office, Cincinnati, OH (1980 f).

Waiwood, K. G., and F. W. H. Beamish: Effects of copper, pH, and hardness on the critical swimming performance of rainbow trout (*Salmo gairdneri* Richardson). Water Res. **12**, 611 (1978).

Walden, C. C.: The toxicity of pulp and paper mill effluents and corresponding measurement procedures. Water Res. **10**, 639 (1976).

_____, T. E. Howard, and G. C. Froud: A quantitative assay of the minimum concentrations of kraft mill effluents which affect fish respiration. Water Res. **4**, 61 (1970).

Waller, W. T., and J. Cairns, Jr.: The use of fish movement patterns to monitor zinc in water. Water Res. **6**, 257 (1972).

Weir, P. A., and C. H. Hine: Effects of various metals on behavior of conditional goldfish. Arch. Environ. Health **20**, 45 (1970).

Weiss, C. M.: Response of fish to sublethal exposures of organic phosphorus insecticides. Sewage Ind. Waste **31**, 580 (1959).

_____ Physiological effect of organic phosphorus insecticides on several species of fish. Trans. Amer. Fish. Soc. **90**, 143 (1961).

Westlake, G. F., H. Kleerekoper, and J. Matis: The locomotor response of goldfish to a steep gradient of copper ions. Water Resources Res. **10**, 103 (1974).

Whittle, D. M., and K. W. Flood: Assessment of the acute toxicity, growth impairment, and flesh tainting potential of a bleached kraft mill effluent on rainbow trout (*Salmo gairdneri*). J. Fish. Res. Board Can. **34**, 869 (1977).

Wildish, D. J., H. Akagi, and N. J. Poole: Avoidance by herring of dissolved components in pulp mill effluents. Bull. Environ. Contam. Toxicol. **18**, 521 (1977).

Zitko, V., and T. D. Cunningham: Fish toxicity of *S*-methyl fenitrothion. Bull. Environ. Contam. Toxicol. **14**, 19 (1975).

Manuscript received June 14, 1982; accepted June 22, 1982.